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ABSTRACT

This report describes studies on natural air motion induced in wide-span educational buildings. It includes a discussion on the influence of air motion indoors on various factors such as the span of buildings, orientation in relation to outdoor wind, open spaces such as courtyards, plan form, semi-partitions, external projections, adjacent buildings of different heights, and landscape elements. A brief description is given of the low-speed wind tunnel and the experimental procedure adopted for this study. The contribution of thermal forces was assessed by an analytical method using experimental data comprising the measurements taken in prototype buildings in the warm, humid season. The report gives design guidelines for inducing air motion and provides diagramatic representations of buildings in relation to air flow patterns. (Author)

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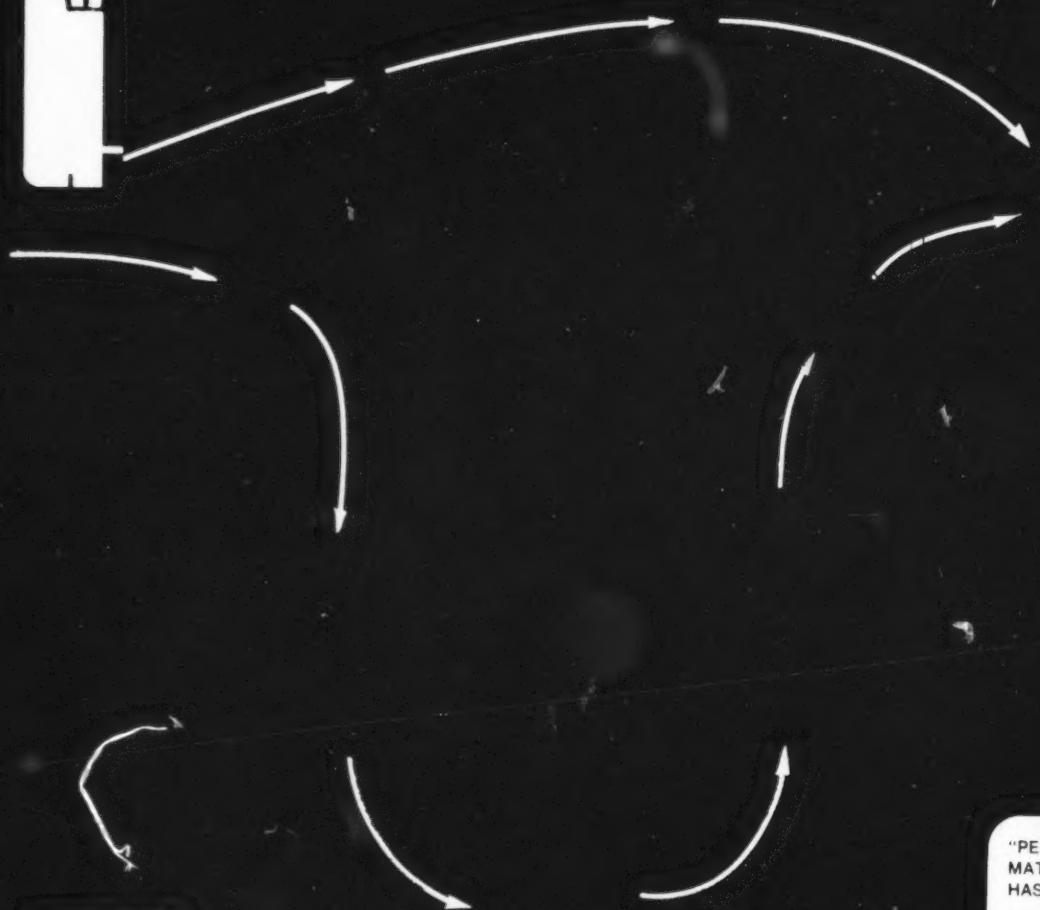

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EDUCATIONAL BUILDING REPORT 6

VENTILATION OF WIDE-SPAN SCHOOLS IN THE HOT, HUMID TROPICS

by Ishwar Chand

UNESCO REGIONAL OFFICE FOR EDUCATION IN ASIA
BANGKOK, THAILAND

The cover drawing is a stylized representation of a unidirectional wind catcher which is an element of traditional house form found near the coasts from Karachi to Cairo.

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FOREWORD

This study was carried out at the Central Building Research Institute, Roorkee, as a project sponsored by Unesco. The Chief Investigator was Dr. Ishwar Chand, Scientist of the Efficiency of Buildings Division in the Institute.

I would like to thank Dr. N.K.D. Choudhury and Mr. R.D. Srivastava, Scientist Co-ordinators of the Institute, who took an active interest in the project and made some useful suggestions. Thanks are also due to Mr. D.J. Vickery, Principal Architect, Unesco, for his active interest in the project and for making useful suggestions during its progress.

DINESH MOHAN
Director
Central Building Research Institute
Roorkee, India

Roorkee, India
19 November 1975

ABSTRACT

Monograph; deals with ventilation of wide-span schools in tropical zones of high humidity; describes experiments with models to study air movement in buildings with and without internal partitions; considers effect of plan form and adjacent buildings on air movement; discusses landscaping and effect on air movement as well as air movement induced by ducts.

This abstract is prepared using descriptors from the Unesco Educational Facilities Thesaurus. The entry can thus be recovered mechanically from Unesco's Computerized Documentation Service facility in Paris, where it is stored.

SUMMARY

This report describes studies on natural air motion induced in wide-span educational buildings. It includes a discussion on the influence of air motion indoors on various factors such as the span of buildings, orientation in relation to outdoor wind, open spaces such as courtyards, plan form, semi-partitions, external projections, adjacent buildings of different heights and landscape elements. A brief description is given of the low-speed wind tunnel and the experimental procedure adopted for this study. Investigations carried out to determine the magnitude of air motion induced by 'stack effect' are also described.

It is shown that buildings can be oriented to the prevailing wind at any appropriate angle between 0^{o} and 30^{o}. When the wind is incident obliquely at angles greater than 30^{o}, the occurrence of dead pockets, that is, wind shadows, may be avoided by providing vertical projections on the wind-facing wall. In building units having openings tangential to the incident wind, air motion indoors can be enhanced by locating another unit in an end-on position on the downstream side. An L-type, continuous lineal arrangement helps to augment air flow in the long wings of buildings.

The leeward half of a wide-span building is a region of very low wind speed. In this part of the building, higher air motion is induced by using semi-partitions with a 0.3-metre space underneath and set across the incident wind.

Air motion in a building shielded by another building of equal height is less than that in a similar unobstructed building. The shielding effect is considerably diminished if the shielded building is taller than the shielding one.

Shrubs and hedges reduce the air motion indoors but trees planted at a distance three times their height in front of the building help to promote air motion in the leeward portion of the building. Earth mounds with a slope of 10^{o} on the upstream side are good promoters of air motion in buildings located on mounds.

It is also established that in a hot humid climate, air motion induced by stack effect in buildings of normal design is too small for comfort.

The report gives design guidelines for inducing air motion and provides diagramatic representations of buildings in relation to air flow patterns.

Chapter One

INTRODUCTION

The thermal comfort of a person is usually defined as "that condition of mind which expresses satisfaction with the thermal environment". People's intellectual and manual performance is generally best when they are comfortable thermally. A primary objective of a building designer, therefore, should be to provide a satisfactory thermal environment indoors. School buildings need special attention in this respect, as it is claimed that the learning capacity of an average student can be increased by from 15 to 60 per cent through the proper design of the indoor environment.[1]

Thermal comfort is governed chiefly by four factors: air temperature, humidity, air speed and radiant heat exchange with the surrounding surfaces. An ideal and constant indoor climate can, of course, always be achieved through the use of mechanical devices—which would, however, involve heavy expense. Therefore the aim should be to design buildings so that indoor conditions are controlled as effectively as possible by natural means.

In a hot, humid climate, the primary comfort requirement is air motion. This should therefore receive first consideration in the design of buildings. Data available in the literature provide basic principles and design guidelines for taking the utmost advantage of the outdoor wind (which is freely available) in isolated enclosures that are one room wide. This information can be used in the design of fenestration in schools having finger-type plans. This type of school has some inherent disadvantages such as the high cost resulting from the construction of long corridors, constraint on the possible internal disposition of the teaching spaces and so on. To achieve a better learning environment, the necessity may arise in future for a change in the shape, size and number of spaces in a building. Such internal free rearrangement can be made only if buildings are designed with spans substantially wider than six metres—say, up to 15 metres.

The design of such wide-span buildings necessitates design guidelines for achieving adequate air motion indoors. Since no such information is available for wide-span buildings, the present study, sponsored by Unesco, was undertaken at the Central Building Research Institute (CBRI), Roorkee, India. The objective of the study is twofold: (1) to examine the influence of various architectural elements such as siting, plan form, open spaces, neighbouring buildings

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1. Z.A. Marsh. "Economics of school heating and air conditioning", *Heat, piping and air condition*, 30(4):157-160, April 1958.

and landscaping on air motion in wide-span buildings, and (2) to provide general design guidelines for school building designers. Furthermore, the feasibility of inducing air motion through the use of solar radiation was also explored.

The investigation was made keeping in view the specific requirements of educational buildings. The results may, however, be made use of in the design of wide-span buildings in general. The study broadly covered the following aspects:

Study of air motion in isolated buildings

1. Effect of the span of buildings
2. Effect of orientation
3. Effect of internal partitions
4. Effect of external projections from the walls

Effect of plan form on indoor air motion, studied in five different configurations

Influence of adjacent buildings

1. Buildings located in broadside-on position
2. Buildings located in end-on position

Influence of landscaping elements

1. Hedges
2. Shrubs
3. Trees
4. Tree and hedge combinations
5. Earth mounds

Study of air motion induced by the stack effect

Chapter Two

EXPERIMENTAL ARRANGEMENTS

The investigation related to air motion induced by aeromotive forces was carried out on models in a low-speed wind tunnel. The contribution of thermal forces (i.e., the stack effect) was assessed by an analytical method using experimental data comprising the measurements taken in prototype buildings in the warm, humid season.

A. Description of the wind tunnel

As shown in Figure 1, the tunnel is an open-circuit, suction type, about 14 metres in length. It has an open-type working section about 2.4 metres wide, 1.8 metres high and 4.5 metres long surrounded by a test chamber 4.8 metres wide, 3.3 metres high and 6 metres long. A heavy wooden table with its top flush with the level of the entry section is placed centrally in the chamber. This acts as the 'ground level' for the building models under test. Air in the tunnel is set in motion using a 1.6 metres axial flow fan with variable pitch blades. The fan is coupled to a 37-kw motor by belts and pulleys of three different diameters. The maximum speed of wind available in the test section is about 40 kilometres per hour. It is varied by the use of a variable-speed, mechanical transmission system and by the adjustment of the variable pitch of the fan blades.

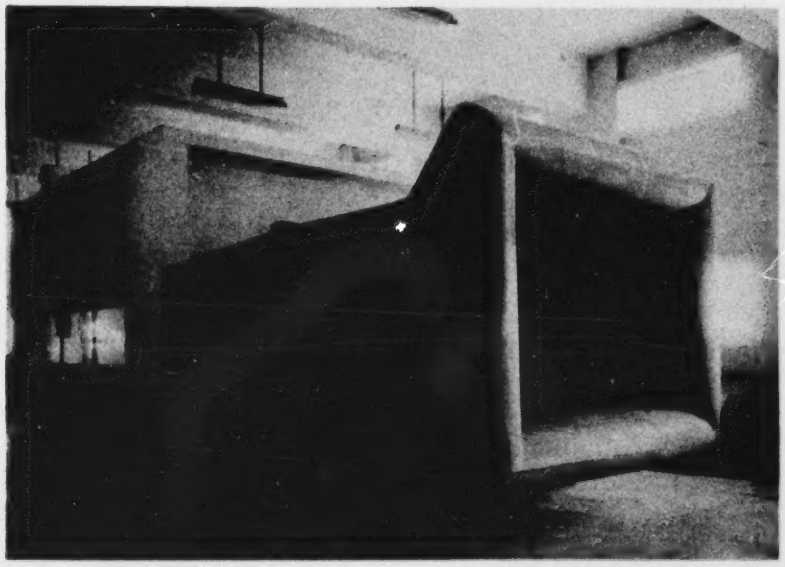


FIGURE 1. THE 2.4 X 1.8 M. LOW-SPEED WIND TUNNEL IN WHICH THE EXPERIMENTAL WORK WAS CARRIED OUT AT THE CENTRAL BUILDING RESEARCH INSTITUTE, ROORKEE, INDIA

B. Models

The models used in this study were scaled-down models of buildings and landscaping elements such as trees, shrubs and hedges. The building models comprised wooden frames covered with plywood sheets. Details of the various models used are given at relevant places in this report.

C. Experimental procedure

In order to have a detailed and informative picture of indoor air motion it is necessary to know the distribution of wind speed at various points inside the building. Accordingly, the sensing probe of an omnidirectional, hot-wire anemometer was placed in the model at a number of points distributed in such a way as to cover the entire occupied area, and the corresponding wind speeds were read directly on the meter. The measurements were taken at work planes 0.5 metres and 1.2 metres above the floor; this covers the normal working zone in schools. Throughout the text of the report the available wind speed has been expressed as percentage of outdoor wind speed, apart from Section VI E dealing with the effect of earth mounds.

Chapter Three

STUDY OF AIR MOTION IN ISOLATED BUILDINGS

This part of the study was aimed at exploring the influence on indoor air motion of factors such as the span of the building, its orientation with respect to the outdoor wind and the presence of semi-partitions and external projections on the building.

A. Effect of the span of buildings

It is well known that the development of air flow patterns inside an enclosure depends in part upon sizes and locations of openings, the speed and direction of oncoming wind, and the dimensions of the enclosure. When other factors are fixed, a variation in the span of buildings results in an alteration of air motion indoors. To study this aspect, experiments were conducted on a 1/20-scale model of a building having its windward wall at an arbitrarily fixed length of 12 metres. Windows were provided on opposite walls. The fenestration area was kept equal to 20 per cent of the wall area and the height of the sill was 0.9 metres above floor level. Wind was incident normally on the model. Indoor wind speeds were measured at several points lying along the central line of the model. Measurements were taken with building spans of 9 metres and 15 metres. The distribution of indoor wind speeds depicted in Figure 2 shows that, as the distance from the inlet increases, the available wind speed at the plane above the sill level decreases, but at levels below the sill, the wind motion first increases and then decreases. It is also noted that the available wind speed decreases as the span of the building is increased, the decrease being greater at points close to the inlet at a workplane lying below the sill level of the windows. This is attributed to the fact that in an enclosure of smaller span, the main incident air stream along with the entrained room air has to travel a smaller distance before reaching the outlet; thus it occupies less room area, leaving sufficient space around it (including the zone below sill level) for the occurrence of return flow approaching the inlet and for the development of eddies. This intensifies the air motion near the inlet at planes below the sill level. At the higher plane the flow is not much disturbed by the return flow of wind and hence is subjected to less change due to alteration in the span of the building. It may be broadly inferred that an increase in span of a building not only results in a smaller value of achievable air speeds in the leeward portion of the building but reduces the air motion in the region close to the inlet opening as well. Such an effect is more pronounced in the zone lying below the window sill.

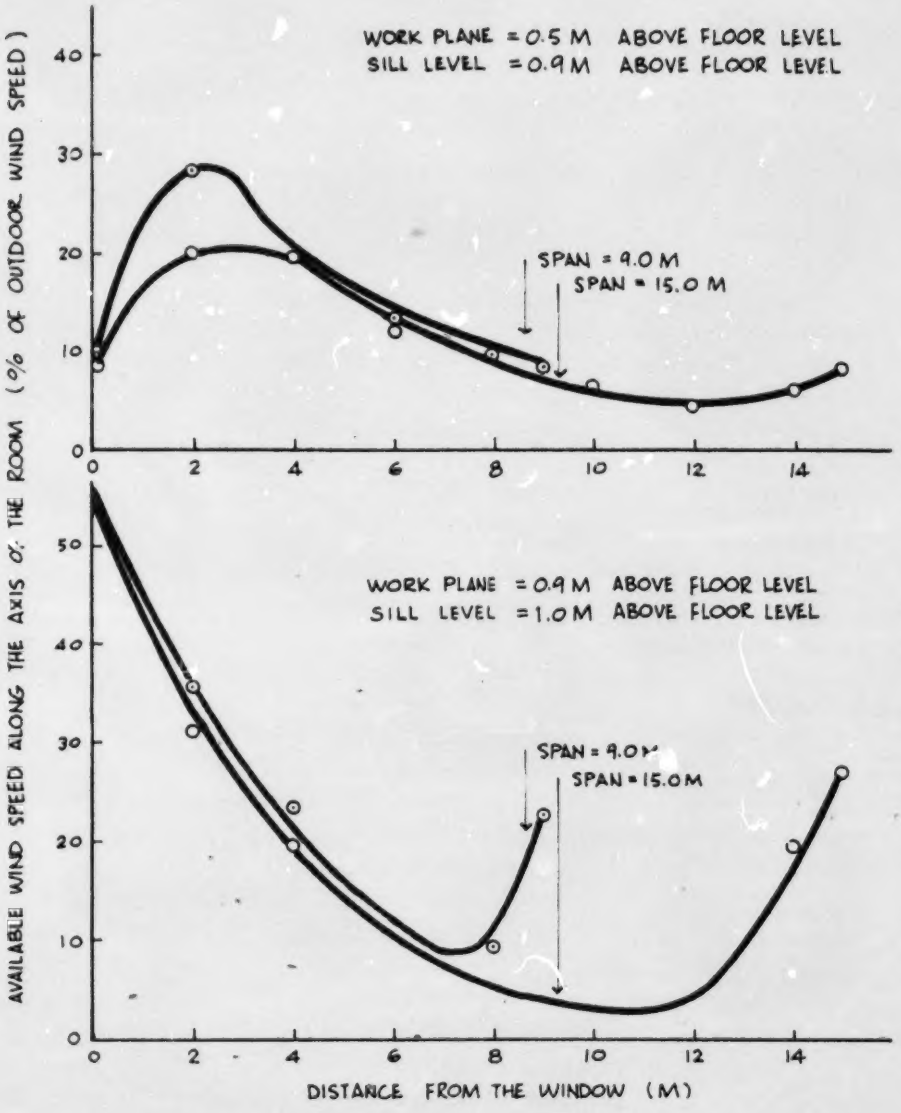

WORK PLANE = 0.5 M ABOVE FLOOR LEVEL
SILL LEVEL = 0.9 M ABOVE FLOOR LEVEL
SPAN = 9.0 M
SPAN = 15.0 M
WORK PLANE = 0.9 M ABOVE FLOOR LEVEL
SILL LEVEL = 1.0 M ABOVE FLOOR LEVEL
SPAN = 9.0 M
SPAN = 15.0 M
AVAILABLE WIND SPEED ALONG THE AXIS OF THE ROOM (% OF OUTDOOR WIND SPEED)
DISTANCE FROM THE WINDOW (M)

FIGURE 2. EFFECT OF INCREASE IN THE SPAN ON AVAILABLE WIND SPEED INDOORS

B. Effect of orientation

Orientation of a building in relation to the direction of wind is an important parameter governing the amount of indoor air motion due to aeromotive forces. A change in wind direction may produce considerable change in the indoor air motion. The magnitude of change produced depends upon the overall dimensions of the building and also on its architectural details.

To establish the influence of orientation, investigations were carried out on building models of finite length, and measurements were taken at a number

of points in the interior of the models. The angle of incidence (measured from the normal to the plane of the window) was varied from 0^{o} to 90^{o} and in each case the average value of indoor wind speed was determined. The results as shown in Figure 3, indicate that at a plane above sill level, the average indoor wind speed increases very slightly, by 0.5 per cent, from 19.5 per cent to 20 per cent of outdoor wind speed, as the angle of incidence changes from 0^{o} to about 30^{o}; beyond that it decreases to about 7 per cent. At a plane below the sill level, air motion decreases slowly at first from 12.5 per cent to 11 per cent up to an incidence angle of 45^{o} and then rapidly as the orientation changes from 45^{o} to 90^{o}. The total reduction from 12.5 per cent to 5 per cent in this zone is much smaller compared to the reduction in the zone above the level of the window sill.

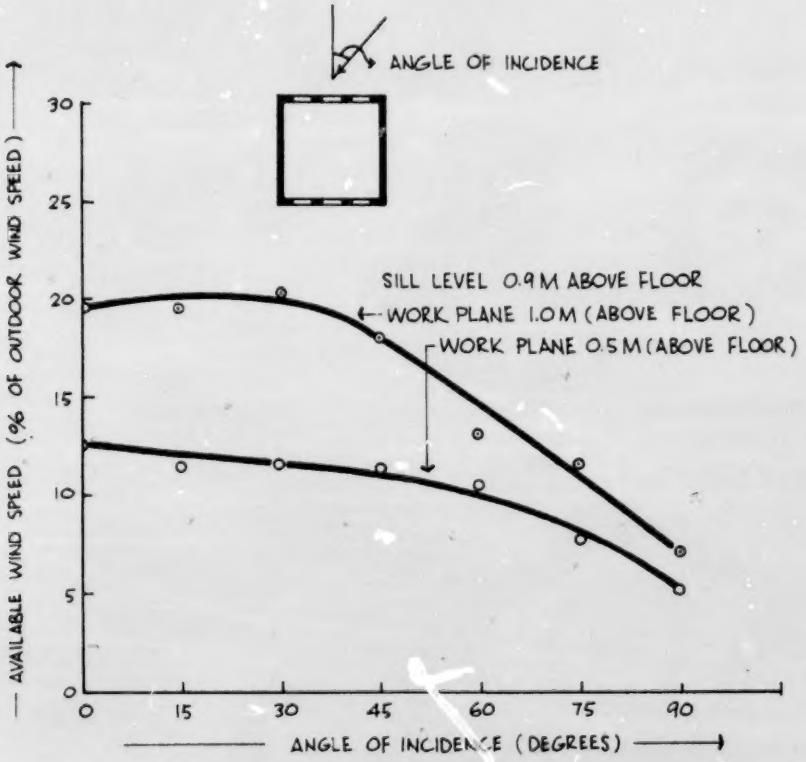


FIGURE 3. EFFECT OF ORIENTATION ON AVERAGE WIND SPEED IN A WIDE-SPAN BUILDING OF FINITE LENGTH

To examine the influence of orientation on air motion in a building of infinite length (i.e. in a building with a length much larger than its height), five models similar in detail to the aforementioned model were joined lineally and measurements taken in the one at the centre. The average indoor wind speeds obtainable for various orientations are plotted in Figure 4. It is observed that in this case also, as the angle of incidence increases from 0^{o} to 30^{o}, the indoor air speed

rises (from 21 per cent to 24 per cent), but further increase in orientation reduces the indoor wind speed.

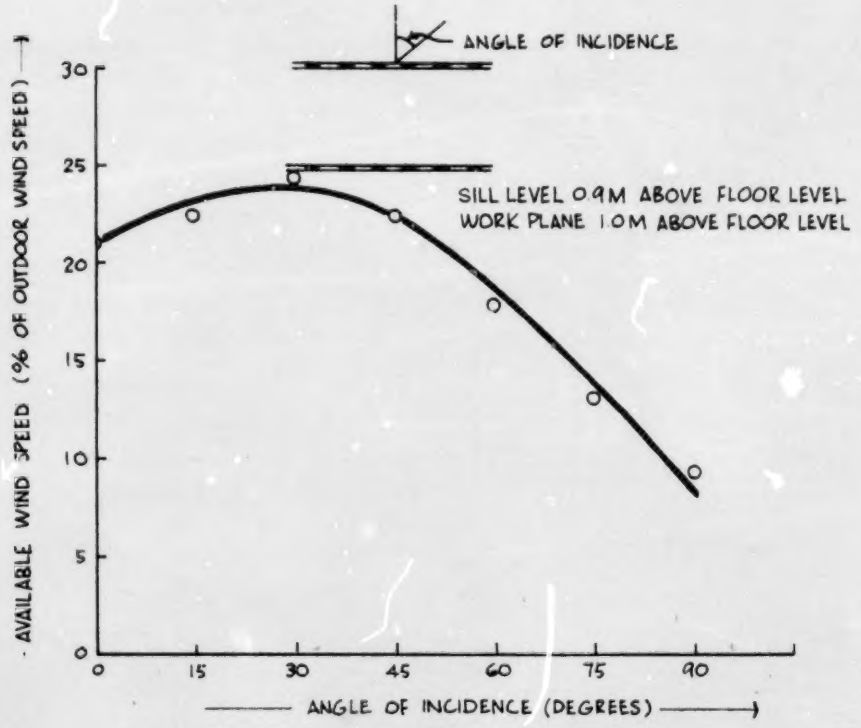


FIGURE 4. EFFECT OF ORIENTATION ON AVERAGE WIND SPEED IN A BUILDING OF INFINITE LENGTH

The tests thus show that the average indoor wind speed at levels above that of the sill is promoted by orienting the building so that the wind strikes the windows at an angle of 30^{o} from the normal to the window plane. For such orientations the reduction in air motion produced in the occupancy zone below the sill level is very slight. To derive maximum benefit from natural wind, therefore, a building need not necessarily be oriented perpendicular to the prevailing outdoor wind: it may be oriented at any convenient angle between 0^{o} to 30^{o} without any significant changes in the breeze's beneficial effect.

C. Effect of internal partitions

Semi-partitions in open-type school buildings are employed primarily to act as an acoustic barrier between two adjacent compartments, as well as to provide visual privacy. Such partitions, when placed parallel to the wind direction, produce slight alteration in the air-flow pattern in the adjoining ar

without affecting the air motion in areas farther away. In wide-span buildings, semi-partitions must be used parallel to the longer sides of the building as well. Partitions located in this manner will obstruct the flow of wind, and the availability of air motion in the building will thus be affected. To examine the role of partitions in governing the distribution of indoor wind speed, experiments were conducted on a model of a 15-metre-span building. A partition was placed at a distance of about 7 metres from the wind-facing wall (Figure 5). Partition heights used were 2.4 metres and 3 metres respectively, the former being the optimum height recommended from an acoustic point of view, and the latter equal to ceiling height - in other words the maximum possible height of a partition. These partitions had a lower clearance of 0.30 metre above floor level to allow the flow of air from one compartment to the next. Available wind speeds indoors were measured at several points along the span of the building. The results are shown in Figure 6.

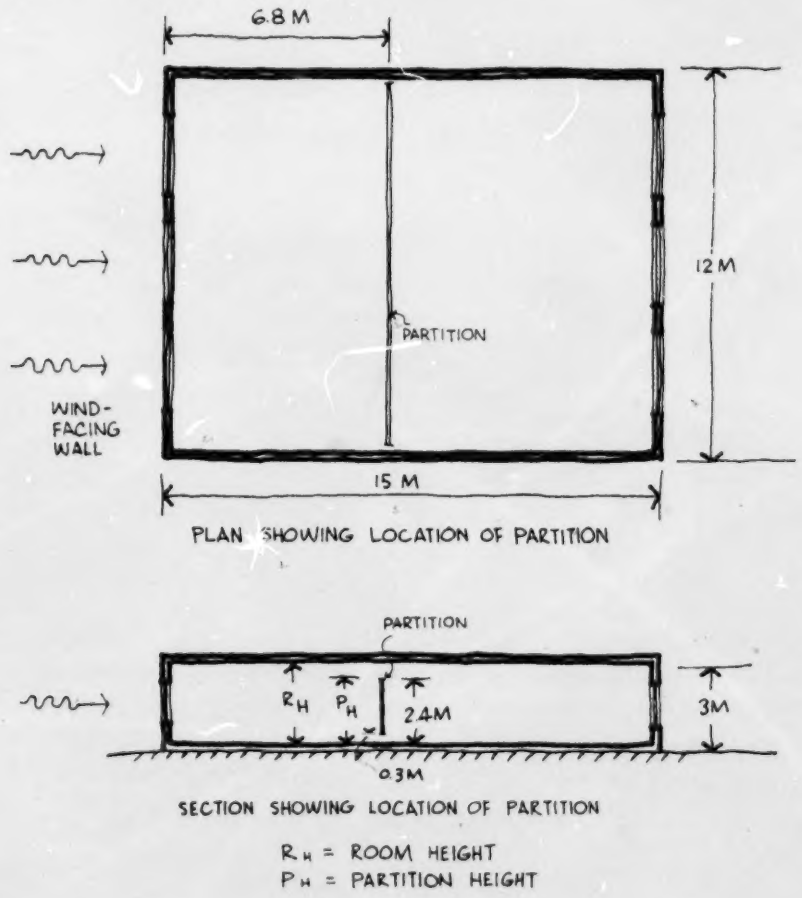


FIGURE 5. LOCATION OF THE SEMI-PARTITION

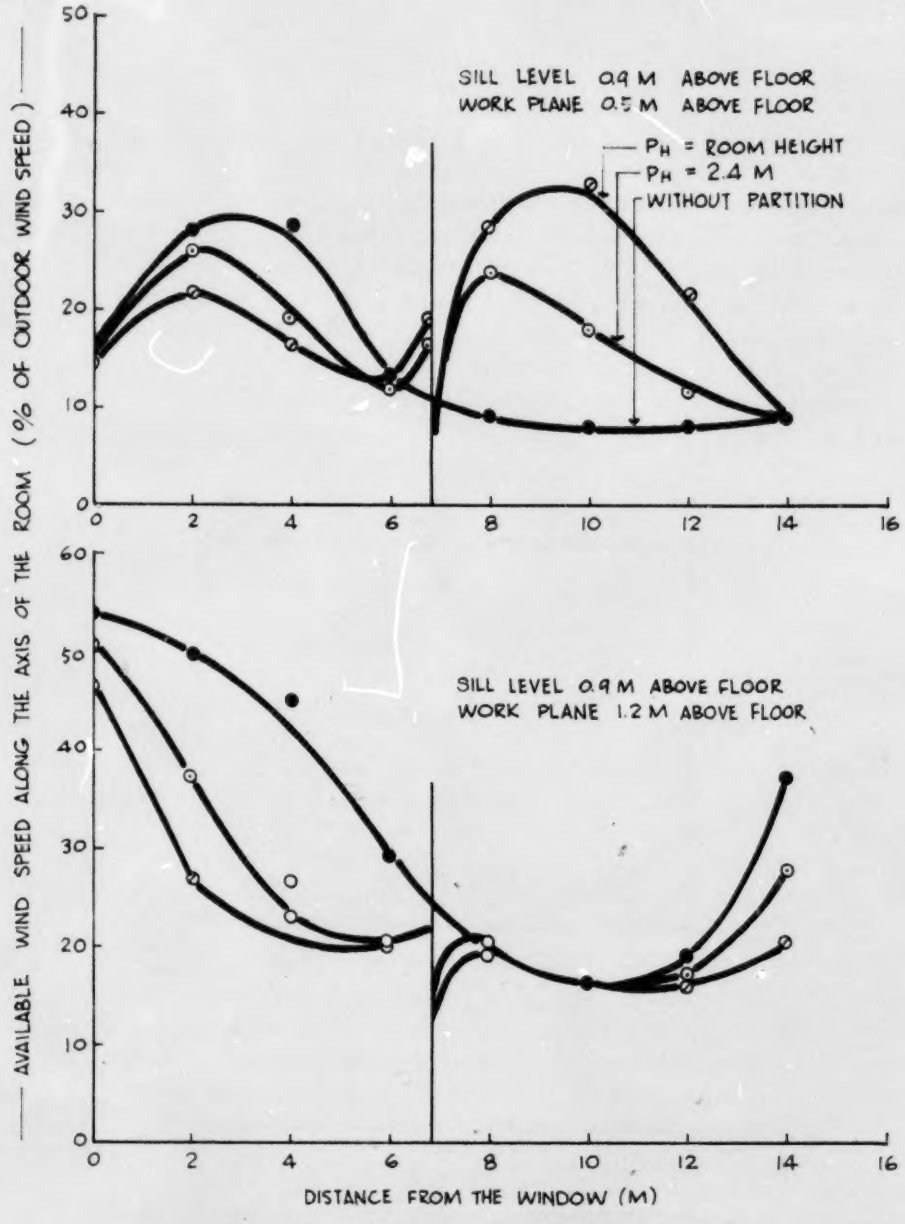

SILL LEVEL 0.9 M ABOVE FLOOR
WORK PLANE 0.5 M ABOVE FLOOR
PH = ROOM HEIGHT
PH = 2.4 M
WITHOUT PARTITION
SILL LEVEL 0.9 M ABOVE FLOOR
WORK PLANE 1.2 M ABOVE FLOOR
AVAILABLE WIND SPEED ALONG THE AXIS OF THE ROOM (% OF OUTDOOR WIND SPEED)
DISTANCE FROM THE WINDOW (M)

FIGURE 6. EFFECT OF THE SEMI-PARTITION ON AVAILABLE WIND SPEED INDOORS

It is seen that air motion at a work plane (W.P.) above the sill level is retarded at all the points inside the windward enclosure due to the use of a semi-partition. Such an effect also occurs in the vicinity of the outlet in the leeward enclosure. It is also noted that the reduction in available air speed increases

with increasing height of the partition. The reduction in indoor air motion is attributable to two factors: (1) the increase in resistance to air flow due to the change in wind direction produced by the partition, and (2) the reduction in the effective area of opening due to the addition of a third opening in series, introduced by the partition. The results pertaining to the measurements taken at the 0.5-metre-level show that wind speed at a level below the sill is reduced in the upstream enclosure, but in the downstream enclosure air motion is considerably enhanced by the application of the partition. Further, the increase in wind speeds in the leeward enclosure is much greater than the reduction in available speeds produced in the windward portion of the building. Such an effect is more pronounced with a partition of greater height. Obviously the downward deflection of air flow caused by the partition and the onward flow of air through the clearance underneath the partition is responsible for promoting air motion at low levels in the downstream enclosures. It was also found that the air motion is not greatly influenced by filling the space underneath the partition with louvres.

Thus it is seen that although semi-partitions introduce a resistance in the air circulations, they are conducive to air motion at low levels in the leeward compartments. Where children sit on the floor in school the openings at the bottom of the partitions can be filled with louvres to ensure visual and acoustic privacy, and at the same time improved air motion can be achieved.

D. Effect of external projections from the walls

The pressures developed on various surfaces of a building due to its interaction with the outdoor wind generate the necessary force for the flow of air through the building. The distribution of wind speed indoors depends upon the difference in pressures acting on both inlet and outlet openings. The magnitude of the motive force is mainly governed by the dimensions of the building, its inclination to the incident wind, and wind speed. However, the pressure distribution on the wind-facing wall is altered by architectural elements such as vertical projections; and this alteration also changes the indoor air motion. To study this effect, experiments were conducted on a model of a single square building 12 x 12 metres in size. The model had identical windows on opposite walls. The air velocity was measured in the centre of the building and also near the two side walls. Wind was incident at 45° to the openings, and observations were made for 16 possible combinations of locations of vertical projections on the wall. The results are summarized in Figure 7. The influence of vertical projections on indoor air motion is also marked on the figure as good or poor.

It is noted that air motion near the upstream wall is increased by vertical projections near this wall. The air motion is further enhanced if another projection is made at a distance of 4 metres from the upstream end. Projections located at greater distances also help to increase air motion indoors, but the gain is less in such cases. It is also found that the velocity indoors is minimum near the upstream wall when there are no external projections on the walls. This velocity is reduced if there is a projection at 4 metres from the upstream end and no projection at the upstream end itself. The projection on the wall near the

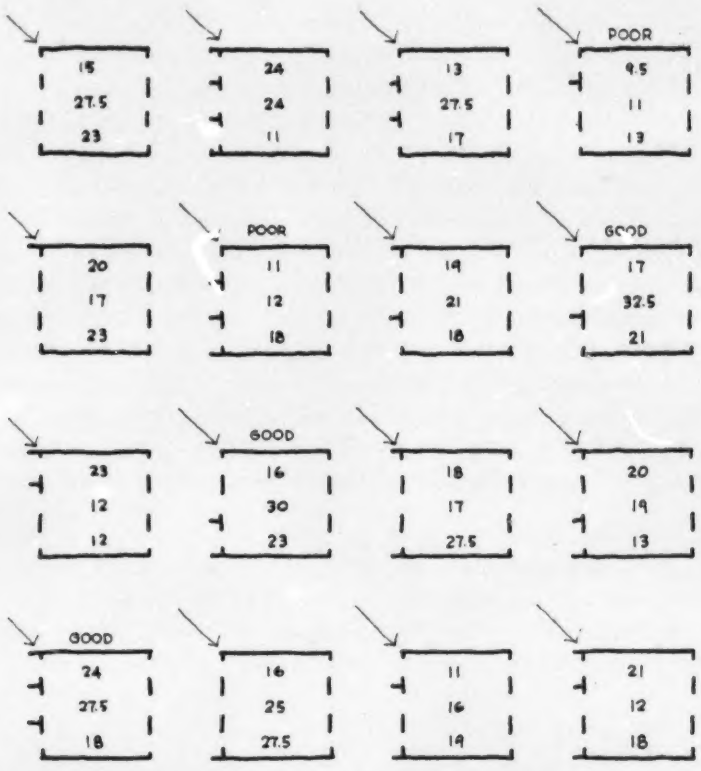


FIGURE 7. EFFECT OF NUMBER AND LOCATION OF PROJECTIONS ON AIR MOTION INDOORS AS % OF OUTDOOR WIND SPEED

upstream end causes a low-pressure region on the wall behind the projection. This in turn deflects the incident wind towards the upstream wall and produces an increase in air motion in a zone which would otherwise lie in the wind shadow of the wall. It is worth noting that projections at 4-metre spacings produce considerable reduction in air motion near the downstream wall. This effect is however reduced by removing the extreme downstream projection.

Similar measurements were also taken for tangentially and normally incident winds. It was found that for these cases external projections on walls do not produce any significant change in indoor air motion.

Thus it is seen that in school buildings where a breeze is needed over the entire occupied area, the occurrence of dead pockets may be avoided by providing external projections on the wind-facing walls. The spacing between the projection should be about 4 metres and their projection about 0.6 metres from the face of the wall. Such projections help induce air motion in the dead zone created by obliquely incident wind; they do not alter air speed distribution indoors for normally or tangentially incident wind. Since the prevailing wind continuously changes direction, outward projections on walls can be of benefit for improving air motion indoors.

Chapter Four

EFFECT OF PLAN FORM ON INDOOR AIR MOTION

The interaction of wind with buildings results in the modification of surrounding air-flow patterns. For a given flow field, the plan form of the building has a bearing on the nature of the encompassing wind motion and governs the pressure distribution on various surfaces of the building. Consequently, the availability of air motion induced inside the various parts of a building is also governed by the shape of the building. Investigations were conducted on a number of typical plans to assess, for a given plan form, the magnitude of indoor air motion induced and to identify situations conducive to air motion indoors. Although these plans represent only a fraction of the many possible plans, their selection is such that the air flow characteristics of practically acceptable situations in school buildings are covered by the tests.

For this study, the distribution of indoor wind speed was determined for angles of incidence of 0^{o}, 45^{o}, 90^{o}, 135^{o}, 180^{o}, 225^{o}, 270^{o} and 315^{o}. The results obtained are shown in Figures 8 to 17.

A. Isolated units

Figure 8 represents a simple case in which two identical building units are joined corner-to-corner. The arrows represent various directions of incident wind and the figures are the corresponding wind speeds expressed as multiples of the speed which was obtainable in an isolated block (Figure 8A) with openings normal to the incident wind. It is seen that available wind speed in a block having windows perpendicular to the incident wind is reduced by 20 per cent when a similar block is located upstream forming an L-shape plan. However, the air motion remains almost unaffected if the block is located downstream. The reduction in air motion in the downstream block occurs because the incident wind is deflected away by the upstream block. When the wind is tangential to the openings, the indoor air motion in the leeward block is not altered but in the upstream block it is considerably increased. It is also found that a change in location of the openings in the leeward block does not produce any change in the air motion induced in the upstream unit. The gain in indoor air motion is obviously a result of the wind pressure developed on inlet openings due to the obstruction of wind flow by the downstream unit. Further analysis of the data shows that for a wind incident at 45^{o} on both the blocks, the wind speed indoors is reduced, the reduction being 35 per cent for inlet openings located on adjacent walls of the two blocks and 65^{o} per cent when they are located on non-adjacent walls. If the wind blowing at 45^{o} to the block is such that one block lies in the wind shadow of the other, the available wind speed in the shielded unit varies from 20 to 30 per cent of the speed

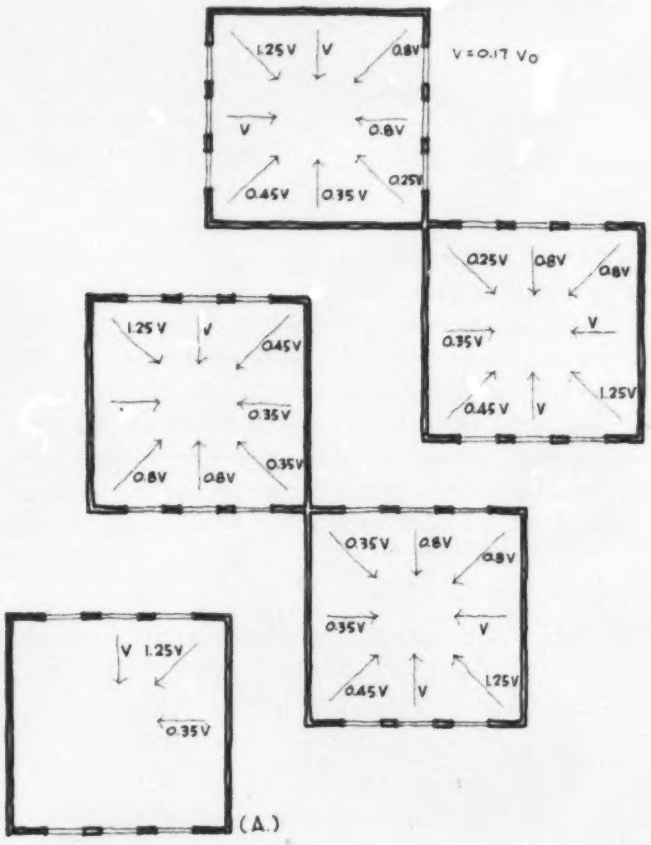


FIGURE 8. WIND SPEEDS AVAILABLE IN SQUARE UNITS LOCATED IN END-ON POSITION

achievable in the shielding unit. Higher air motion is induced when the location of windows is such that the flow in both the blocks is in a similar direction.

Thus it is seen that when square units are arranged in the end-on position to form a part of the plan of a school building, the inlet openings should be located on adjacent walls of the blocks and outlet windows should be provided on opposite walls. Such a provision of openings will help to induce air motion indoors for tangentially incident winds as well.

B. L-Shape plan

Figure 9 depicts a plan in which a long building has attached to it a side wing of much smaller length. To study the influence of this side wing on air motion induced in various zones of the longer wing, the average wind speeds were determined at five locations. Similar measurements were taken by detaching the smaller wing, and the value of the wind speed was used as a reference in terms of which the results of the afore mentioned measurements were expressed. It is observed that when wind is incident parallel to the longer wing, the presence of

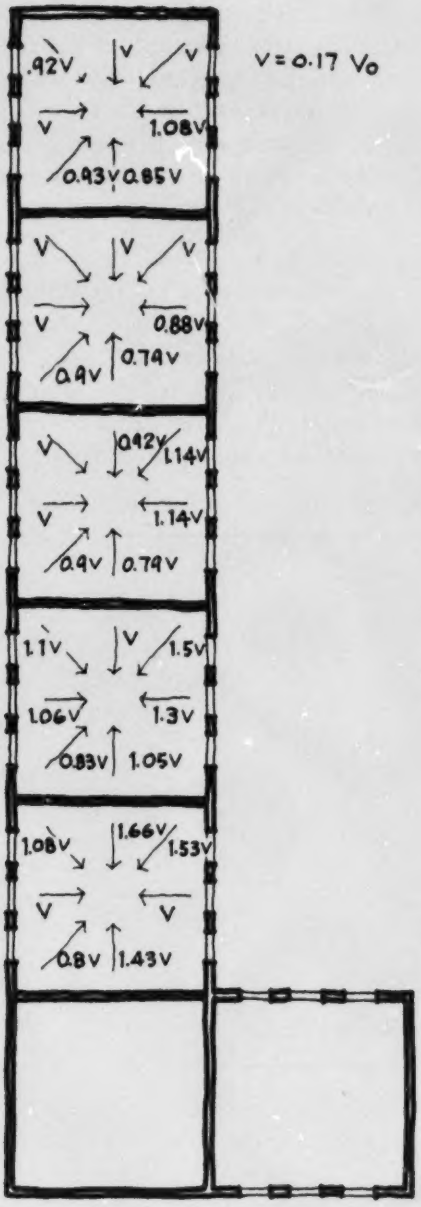


FIGURE 9. WIND SPEEDS AVAILABLE IN A BUILDING WITH L-SHAPE PLAN

a perpendicular smaller wing promotes air motion only in the adjacent parts of the longer wing without influencing air motion in its remote areas. Similar increase in air motion occurs when the smaller wing is on the upstream side. In this case a retardation is also produced in the air motion in the downstream region of the building. It is also seen that when wind strikes the longer wing normally, the indoor air motion is not affected by the presence of the adjacent wing on the leeward side; but it is promoted by about 20 per cent in the central

region due to the windward location of the wing. In the case of oblique winds, an increase in air motion is produced in the entire building, when wind strikes on both the wings on the inner side of the plan. The increase varies from 10 to 50 per cent, being maximum in the downstream zone. For a 180^{o} variation in wind direction, the presence of a smaller wing produces a reduction in wind speeds indoors; the reduction varies from 20 per cent in the upstream region to 10 per cent in the downstream portion of the building.

The influence of increase in the length of the side wing was investigated by measuring indoor wind speeds in a model of a building having wings each 45 metres in length. A comparison of the results, shown in Figure 10, with the earlier measurements shows that an increase in the length of the side wing helps to promote indoor air motion over a greater region of the building when windows are tangential to the oncoming wind. For other orientations of the building the influence on air motion remains almost the same.

Thus it is seen that air motion in the long wing of a building can be enhanced by locating a block normally at one end of the wing and orienting the building so

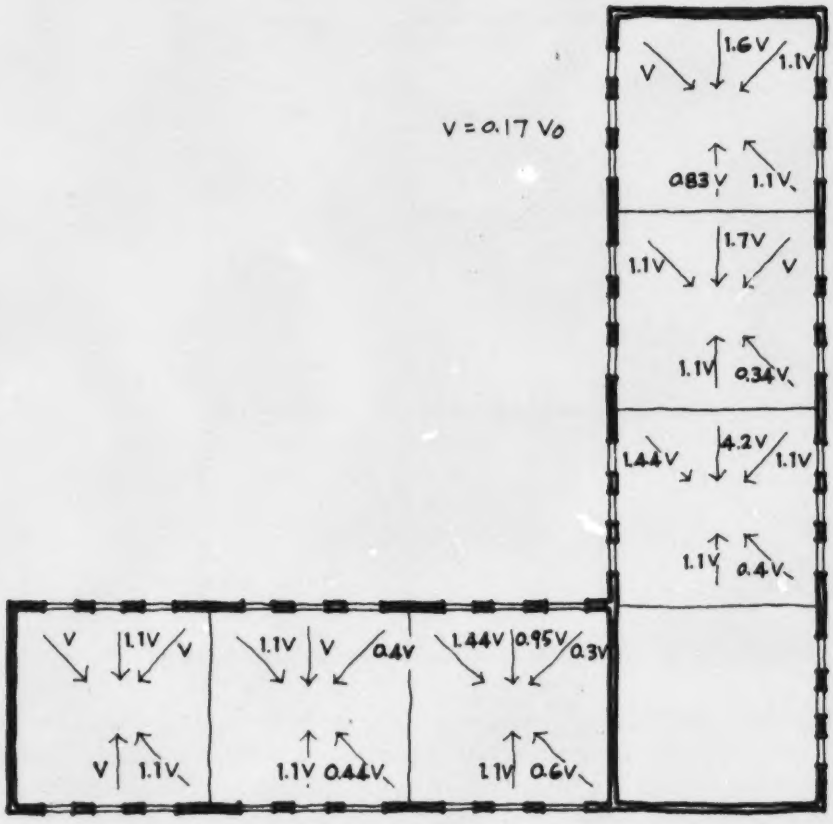


FIGURE 10. EFFECT OF INCREASING THE LENGTH OF THE SMALLER WING OF A BUILDING WITH AN L-SHAPE PLAN

that wind strikes obliquely on both the wings from the inner side of the (L-shape) plan.

C. U-shape plan

This type of plan is formed by building a wing which joins the ends of two parallel wings. Air motion induced in various zones of the building depends on the length of the connecting block and also on the direction of the incident wind. To assess the influence of these factors, experiments were conducted on models arranged to form a U-shape plan. The length of the end block was 15 metres, and the indoor wind speed measurements were taken for different wind directions. The results are shown in Figure 11. It is seen that this arrangement helps to increase air motion in the zones of the longer limbs adjacent to the connecting limb for an incident wind parallel to the channel formed by the longer wings. For wind incident at 45°, the air motion is reduced not only in the leeward wing (which is shielded by the other wing) but in the windward wing as well. This is probably because of the higher pressure developed on the leeward face of the wind-facing block due to the obstruction of wind flow between the wings.

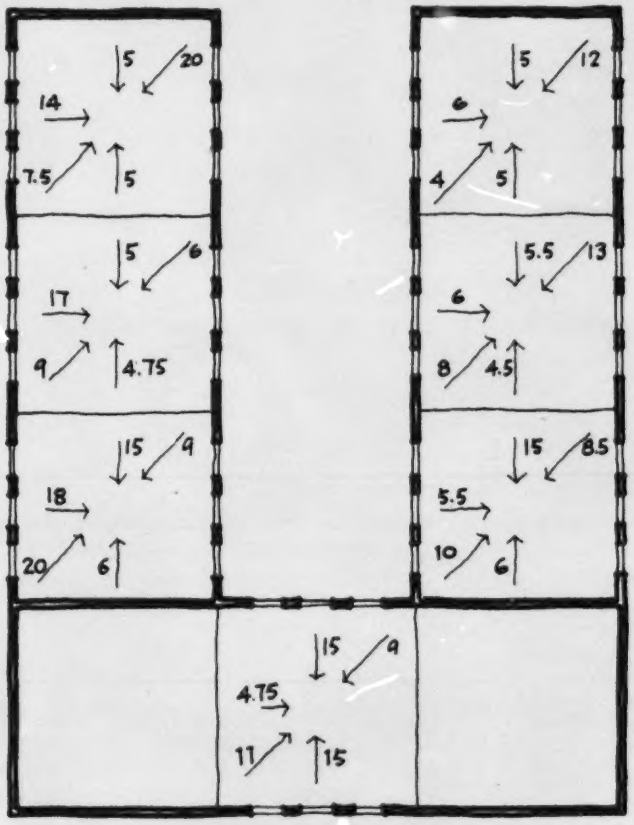


FIGURE 11. WIND SPEEDS AVAILABLE IN A BUILDING WITH U-SHAPE PLAN AS % OF OUTDOOR WIND SPEED

To examine the influence of the length of the connecting block, indoor wind-speed distribution was determined for normally incident wind in models of buildings having connecting blocks 15, 30 and 45 metres long respectively. The available indoor wind speeds for these cases are shown against the numbers 1, 2 and 3 in Figure 12. It is observed that by increasing the length of the connecting wing, the air motion in the longer wings is increased. Maximum benefit is achieved in the downstream region and very little advantage is obtained in the upstream region of the parallel wings.

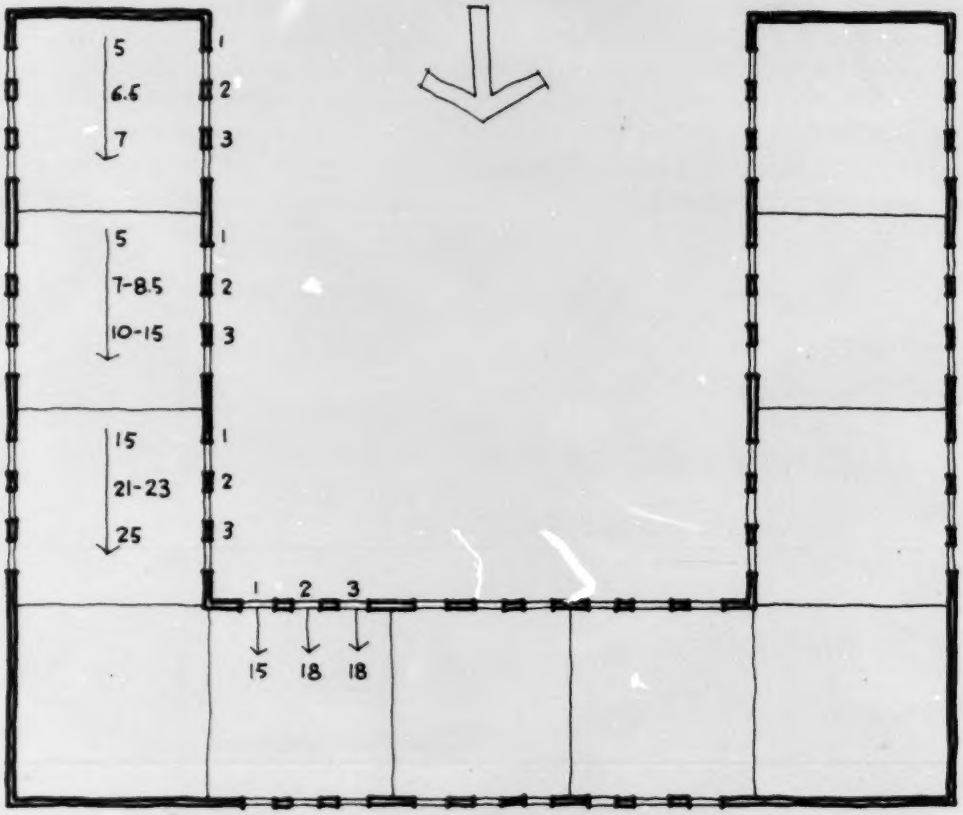


FIGURE 12. EFFECT OF INCREASING THE LENGTH OF CONNECTING WING OF A BUILDING WITH U-SHAPE PLAN. WIND SPEED EXPRESSED AS % OF OUTDOOR WIND SPEED

Thus it is found that buildings having a U-shape plan have the benefit of higher induced air motion in situations where, due to other considerations, the building has to be oriented so that the wind is incident parallel to their openings.

D. H-shape plan

In this case two parallel wings have a central connecting wing. The air motion achievable in different parts of the building for various wind directions was examined as in earlier cases and results are shown in Figure 13. An

analysis of the data indicates that, when wind is incident normally or obliquely on the parallel wings, the latter shield the remaining part of the building so that very little air motion is induced there. It is also noted that, when wind blows parallel to the two wings, higher air motion is induced in the region of the parallel wings located near the central wing on the upstream side; but because of the shielding created by the central wing, air motion in the leeward portion is considerably reduced.

It is thus seen that buildings having an H-shape plan are self-shielding and do not conduce to the induction of air motion indoors.

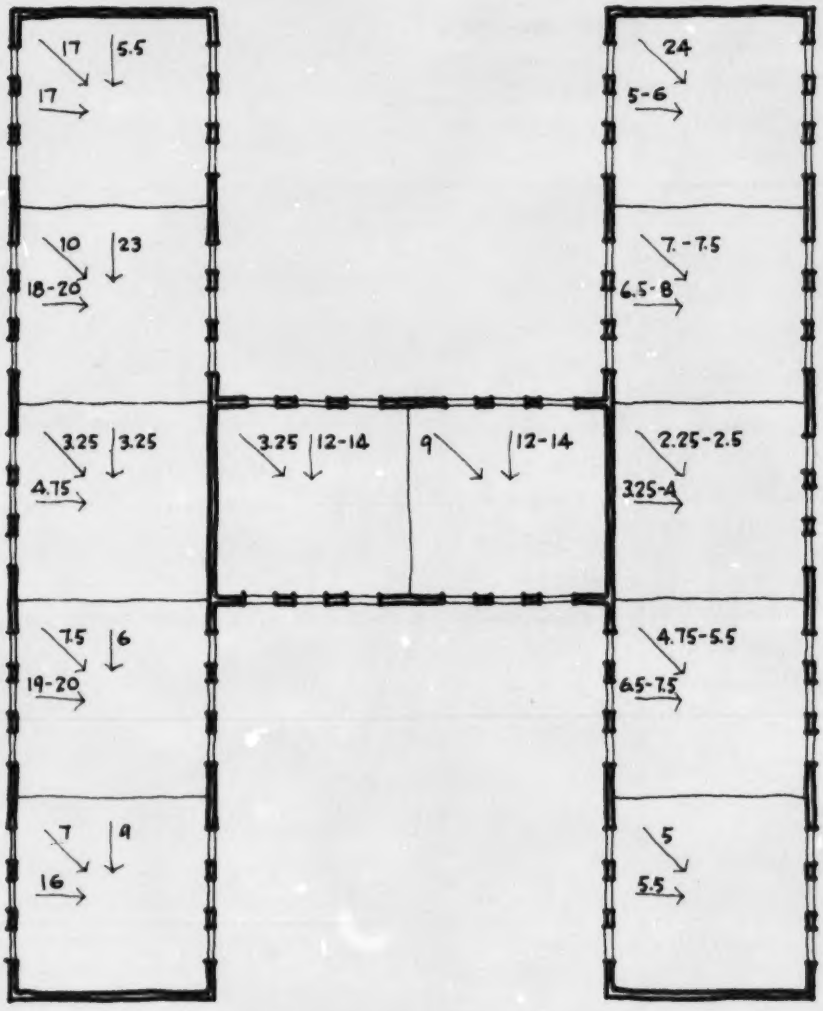


FIGURE 13. WIND SPEEDS AVAILABLE IN A BUILDING WITH H-SHAPE PLAN AS % OF OUTDOOR WIND SPEED

E. T-shape plan

This arrangement consists of a long wing having a centrally connected smaller wing. Figure 14 shows the available indoor wind speeds when the building is oriented at different ang'es to the incident wind. A comparison of the findings with the results of the H-shape plan shows that the 'T' shape induces higher air motion indoors for obliquely incident wind. It is also noted that, when wind flows parallel to the central wing, the air motion induced therein is not as high as with the L-shape.

Thus it is observed that the T-shape plan form will help promote air motion only in a limited part of the buildings.

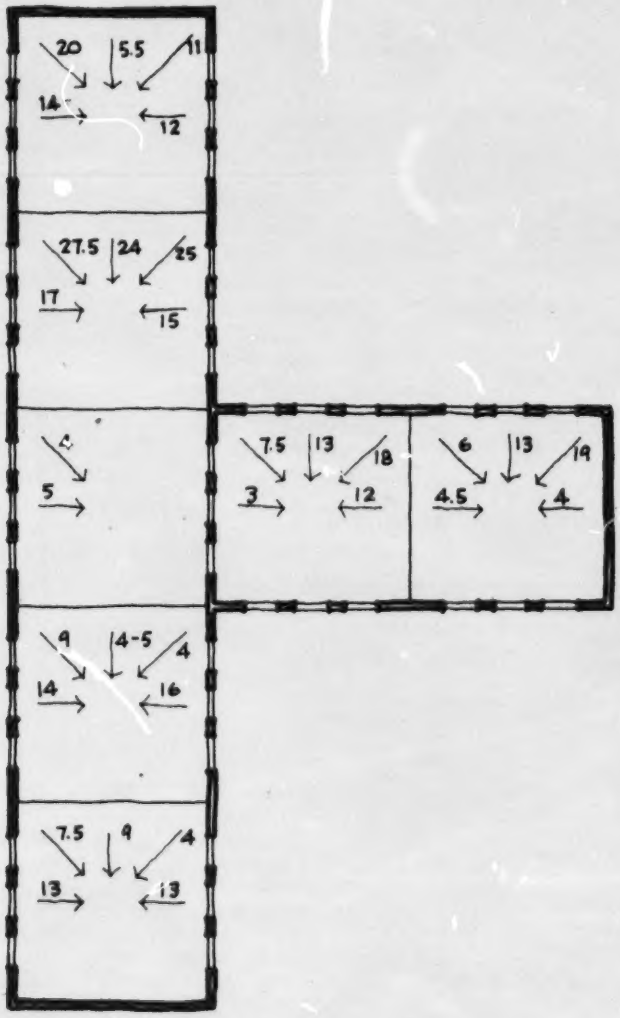


FIGURE 14. WIND SPEEDS AVAILABLE IN A BUILDING WITH T-SHAPE PLAN AS % OF OUTDOOR WIND SPEED

F. Cross-shape (+) plan

Two long buildings were joined centrally at right angles to form a cross-shape plan. The distribution of indoor wind speeds shown in Figure 15 indicates that, for most of the situations, the induced air motion is less than that induced in an isolated row of buildings. The reduction is probably because the wind is deflected by the windward part of the building in such a way that the rest of the building lies in the region of wind shadow.

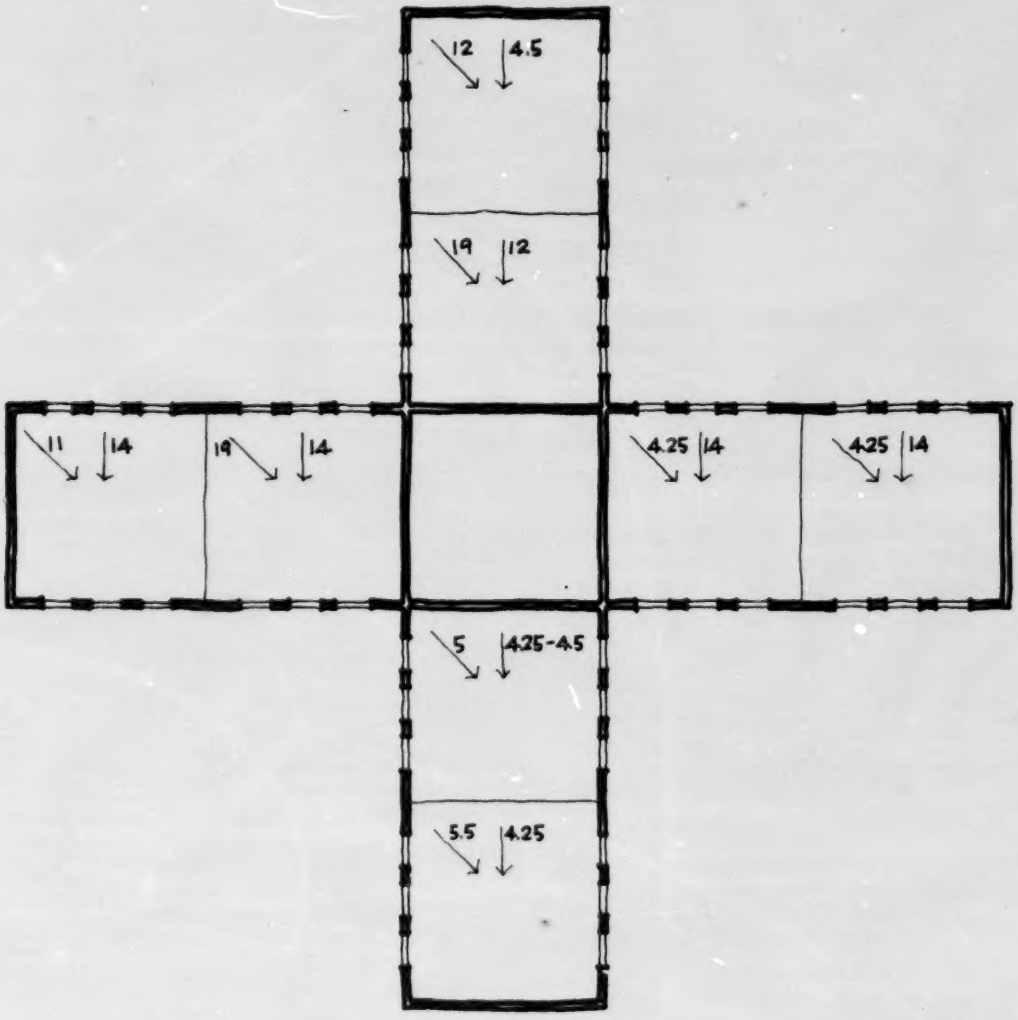


FIGURE 15. WIND SPEEDS AVAILABLE IN A BUILDING WITH CROSS-SHAPE PLAN AS % OF OUTDOOR WIND SPEED

G. Study of the influence of courtyards on indoor air motion

The experimental arrangement consisted of 12 models of five-storey square blocks 15 x 15 metres in plan. These were arranged in four rows in alternate positions to form square courtyards (15 x 15 metres) between them. Thus the arrangement had four courtyards, each surrounded by four building blocks in the central rows and six courtyards surrounded on three sides by the building blocks in the outer rows. (see Figure 16). Each block was provided with openings on two sides, one facing the courtyard and the other opposite to it. The height of the blocks was 15 metres. The wind was incident at 0°, 45° and 90° and indoor wind speeds were measured in the lowest blocks. The study examined two types of courtyards, the 'open' type and a 'closed' type. In the open situation the building blocks were supported on stilts. From Figures 16 and 17 it can be seen that when wind is incident normally on the windows, very little air motion is induced in the blocks located in the leeward rows; also, the nature of the courtyard (open or closed) does not produce any significant change in the wind motion achieved in it. However, greater wind speeds are obtained in windward blocks when the courtyard is of an open type. It is also seen that for wind incident tangentially on windows, closed courtyards produce a considerable increase in air motion in the windward block, but in other blocks very little air motion is induced for both types of courtyards. For oblique winds, higher air motion occurs in the wind-facing blocks with the open type courtyard, and in the leeward blocks with courtyards of the closed type.

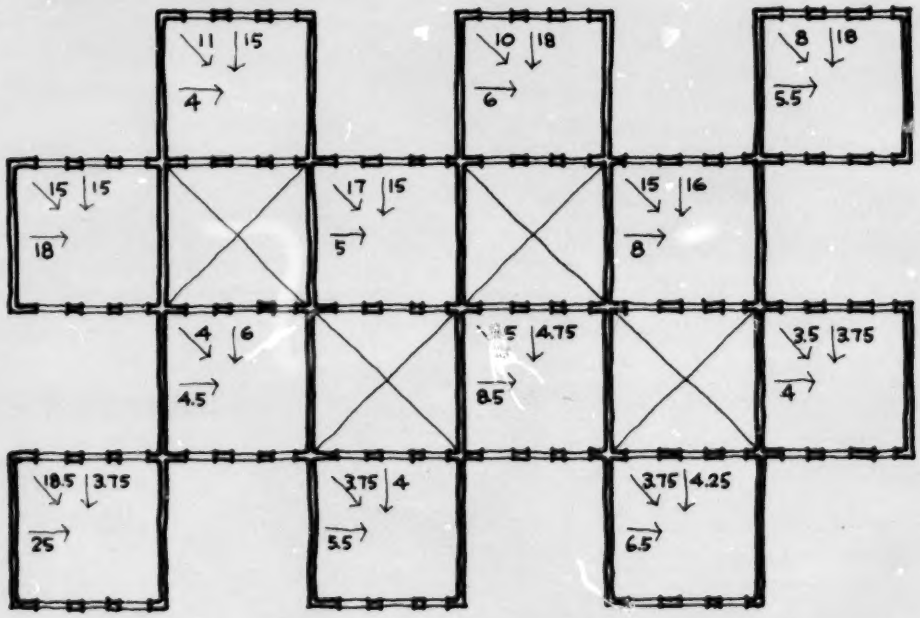


FIGURE 16. WIND SPEEDS AVAILABLE IN DIFFERENT BLOCKS OF A BUILDING HAVING CLOSED COURTYARDS AS % OF OUTDOOR WIND SPEED

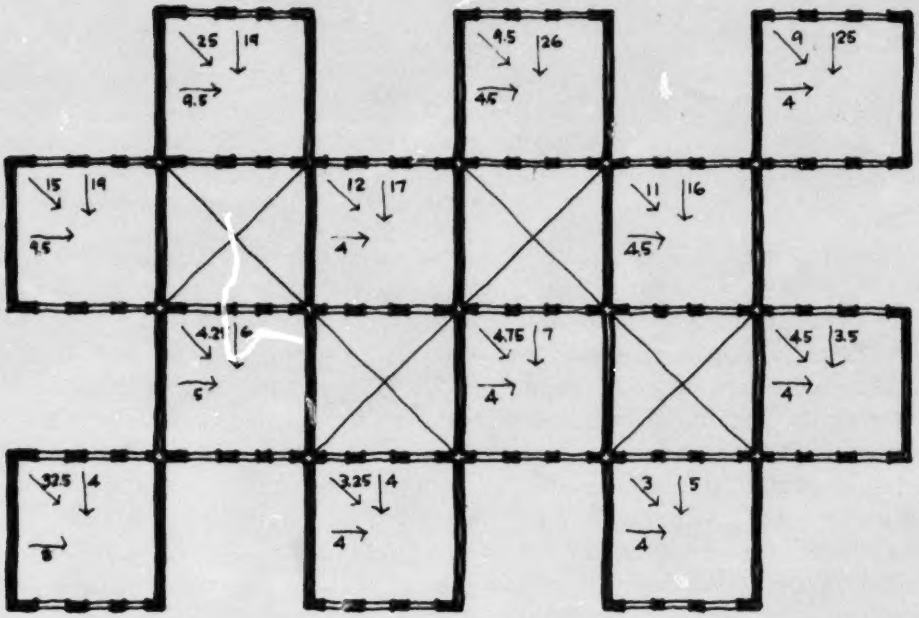


FIGURE 17. WIND SPEEDS AVAILABLE IN DIFFERENT BLOCKS OF A BUILDING HAVING OPEN COURTYARDS AS % OF OUTDOOR WIND SPEED

Thus the provision of courtyards (open or closed) between the blocks does not help induce wind motion in the shielded units of the building. However, closed courtyards perform better as regards inducing air motion in the shielded blocks.

Finally, the study of the effect of plan form of a building on indoor air motion shows that the various components of a building may help in the enhancement of air motion indoors in situations when building orientation is such that wind does not strike the windows within the optimum angle of 30° to the normal. The different components may be coupled in such a way that, by deflecting the outdoor wind, air motion in the desired zone is induced without shielding any part of the building. This can be achieved by a continuous L-shaped linear arrangement of units as shown in Figure 18.

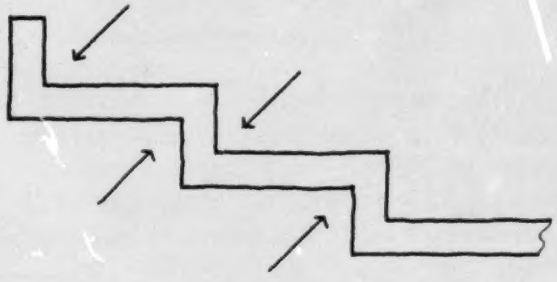


FIGURE 18. L-TYPE, LINEAR ARRANGEMENT OF UNITS

Chapter Five

INFLUENCE OF ADJACENT BUILDINGS

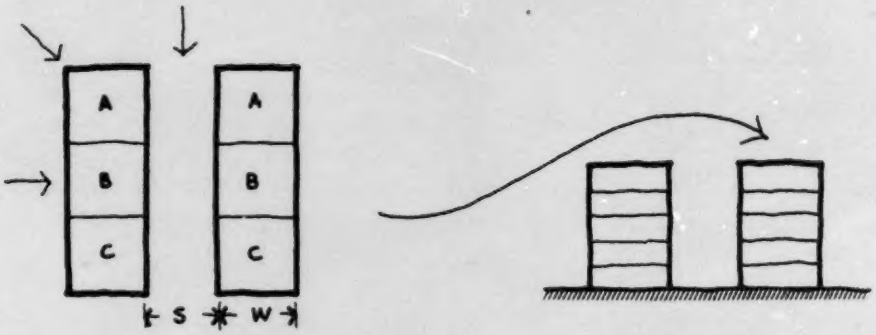
The data reported earlier make it possible to predict the amount of air motion induced by wind force in buildings exposed directly to the incident wind. Because of alterations in the flow characteristics of the oncoming wind, however, these results cannot be used for assessing probable air motion in buildings which have other buildings in the neighbourhood. A study was carried out, therefore, to discover the pattern of indoor air motion in buildings grouped together. The influence of a building on the air motion in an adjacent building depends upon the dimensions of the buildings and their location with reference to the direction of the incident wind. Although innumerable plans are possible, in all situations buildings are located either end-on or in broadside-on positions. To examine a practical layout of educational buildings, the present study was carried out for buildings arranged in parallel rows.

The experiments were conducted on models of buildings with a span of 15 metres. The length of the blocks was restricted to 45 metres which was large enough relative to their span. The wind was incident at 0^{o}, 45^{o} and 90^{o} on the long walls of the blocks. The distance of separation (S) between the blocks was varied from 0.5 to 3 times the span of the block (W) and in each case the average indoor wind speed was determined in the centre of the blocks and also near the two end walls. The study considers various arrangements of the buildings in relation to each other.

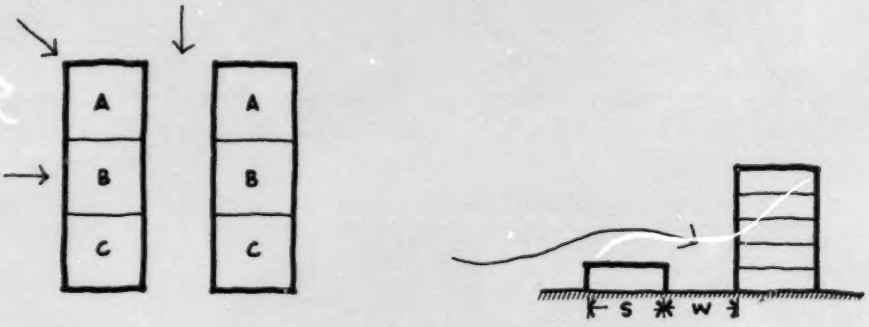
A. Buildings located in broadside-on position

1. Blocks of equal heights. In this case, identical models representing five-story buildings were placed parallel to each other with their end walls lying in a straight line /Figure 19 (a)/. The results, summarized in Table 1, indicate that for normally incident wind, air motion in windward blocks is independent of the distance of separation betwen the two rows; but in leeward blocks it increases as the separation is increased. For oblique winds (45^{o} incidence), the air motion in the wind-facing block and also in the downstream zones of leeward blocks is increased when spacing between the rows is increased. However, air motion in the upstream zone of a shielded row increases as it approaches the shielding blocks. This is probably because the wind, accelerated due to the deflection of the edge of the windward block, strikes the upstream edge of the leeward blocks when the spacing is small. As the spacing increases, the deflected air stream strikes at the downstream side of the shielded row and intensifies indoor air motion in the respective zones. It is also observed that for tangentially incident wind, very little air motion is induced indoors; moreover, this is not much affected by changing the spacing between adjacent rows.

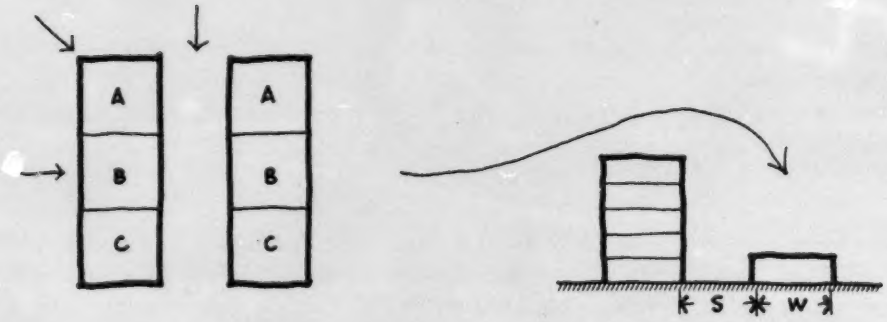
FIGURE 19



a) BUILDINGS OF EQUAL HEIGHT LOCATED IN BROADSIDE-ON POSITION



b) A FIVE-STOREY BUILDING LOCATED ON LEEWARD SIDE OF A SINGLE-STOREY BUILDING



C) A FIVE-STOREY BUILDING LOCATED ON WINDWARD SIDE OF A SINGLE-STOREY BUILDING

Table 1

Available wind speeds indoors when buildings of equal height are located in broadside-on position, shown as per cent of outdoor wind speed

θ^{o}	Block Location		Distance between blocks				
			0.5 W	1.0 W	1.5 W	2.0 W	3.0 W
0^{o}	Windward	A	17.0	17.0	16.0	17.0	17.0
		B	20.0	20.0	20.0	20.0	20.0
		C	13.0	13.0	13.0	13.0	13.0
	Leeward	A	3.0	4.5	6.0	7.5	8.0
		B	4.5	4.5	6.0	7.5	8.0
		C	3.0	4.5	6.0	7.0	8.0
45^{o}	Windward	A	27.5	32.5	35.0	35.0	32.5
		B	11.0	14.0	15.0	15.0	15.0
		C	10.0	12.0	12.0	12.0	12.0
	Leeward	A	30.0	27.5	22.5	22.5	22.5
		B	3.7	3.7	4.0	7.0	12.5
		C	3.0	3.5	3.0	4.5	6.0
90^{o}	Windward	A	4.5	6.0	6.0	5.5	4.5
		B	5.0	8.5	8.5	10.0	8.0
		C	4.5	5.0	4.5	5.5	5.5

NOTE : In Tables 1 to 5, W = internal span of the block, and θ = angle of incidence of the wind.

Thus it is seen that identical blocks arranged in parallel rows, with their ends in a straight line, create poor ventilation conditions in the shielded blocks. Here, better conditions can be achieved by keeping the distance of separation more than ten times the height of the blocks as established by the earlier work carried out in C.B.R.I. [1]

2. Blocks of different heights. To examine the amount of air motion induced in blocks of unequal heights, tests were conducted on models of single and five storey blocks; the former was located on the windward side and the latter on the leeward. This represents a situation in which a low building is situated on the

1. Ishwar Chand and others. "Studies of air motion in shielded buildings", *The Indian Engineer*, XIX(9):23-29, September 1975.

upstream side of a multi-storey building /Figure 19 (b)/. The results of the study are summarized in Table 2. It is seen that for normally incident wind, air motion in the central part of the windward row is considerably increased by increasing the distance of separation up to 1.5 W; beyond that it becomes almost constant. However, in leeward blocks air motion is not affected much by changing the location of the blocks. For oblique winds, the increase in the distance of separation to 2 W promotes air motion in the upstream part of the windward building; in the remaining part, air motion is quite small for all locations of the building. In the leeward block, air motion is reduced in the downstream zones if the building is moved farther away from the shielding block. It is also noted that air motion is enhanced in the upstream part of the single-storey building, and also in the downstream part of the multi-storey building, when the spacing between the blocks exceeds 0.5 W. In other parts of the building, air motion is much less and does not vary in a systematic manner with the change in the spacing between the rows.

Table 2

Available wind speeds indoors where a five-storey building is located on the leeward side of a single-storey building, shown as per cent of outdoor wind speed

θ^{o}	Block Location		Distance between blocks				
			0.5 W	1.0 W	1.5 W	2.0 W	3.0 W
0^{o}	Windward	A	11.0	14.0	14.0	14.0	14.0
		B	6.0	8.0	12.0	14.0	14.0
		C	12.0	14.0	14.0	14.0	14.0
	Leeward	A	15.0	17.0	17.0	17.5	16.0
		B	18.0	18.0	18.0	18.0	17.0
		C	14.0	15.0	15.0	15.0	14.0
45^{o}	Windward	A	4.0	5.0	5.5	16.0	12.0
		B	4.25	2.7	3.5	4.2	5.0
		C	6.0	6.0	3.7	3.5	4.5
	Leeward	A	17.0	17.0	18.0	17.0	15.0
		B	16.0	15.0	16.0	16.0	21.0
		C	16.0	12.0	12.0	12.0	10.0
90^{o}	Single Storey	A	5.5	8.5	11.0	11.0	11.0
		B	3.25	3.25	2.7	2.5	3.7
		C	2.0	2.5	2.0	1.5	2.0
	Five Storey	A	5.5	4.7	4.2	3.7	4.0
		B	6.0	8.5	8.5	7.0	8.0
		C	4.5	6.0	8.0	6.5	7.0

Thus it is inferred that to achieve better ventilation indoors, the separation between a multi-storey block and a windward, single-storey block should be kept to about twice the span of the building.

Table 3 represents the achievable indoor wind speeds when a single-storey building is shielded by a five-storey building is shielded by a five-storey building /Figure 19 (c)/. For normally incident winds, air motion in the windward block is almost constant but in the single-storey, leeward block it increases slightly with the increase in spacing between the blocks. For oblique winds, the air motion in the upstream part of the windward block is enhanced when the distance of the leeward block is increased from 0.5 W to 3.0 W, but in the other parts of the building it is almost independent of the location of the two blocks. It is also observed that shifting of the blocks away from each other reduces air motion in the upstream part of the leeward block and promotes it in the central portion. However, in the downstream region of the shielded block, air motion first decreases and then increases as the block is shifted away from the shielding building.

Table 3

Available wind speeds indoors where a five-storey building is located on the windward side of a single-storey building, shown as per cent of outdoor wind speed

θ^{o}	Block Location		Distance between blocks				
			0.5 W	1.0 W	1.5 W	2.0 W	3.0 W
0^{o}	Windward	A	17.0	18.0	18.0	18.0	18.0
		B	22.0	22.0	22.0	22.0	22.0
		C	17.0	16.0	17.0	17.0	17.0
	Leeward	A	4.0	4.5	4.7	5.0	6.5
		B	4.0	4.7	5.0	6.0	9.0
		C	4.0	4.5	4.7	5.5	7.5
45^{o}	Windward	A	27.5	30.0	30.0	30.0	30.0
		B	21.0	21.0	21.0	21.0	21.7
		C	12.0	12.0	13.0	13.0	13.0
	Leeward	A	35.0	11.0	10.0	23.0	10.0
		B	3.0	3.0	4.0	6.0	6.0
		C	4.7	6.5	5.5	4.7	3.5
90^{o}	Five-Storey	A	5.5	4.7	4.2	3.7	4.0
		B	6.0	8.5	8.5	7.0	8.0
		C	4.5	6.0	8.0	6.5	7.0
	Single-Storey	A	5.5	8.5	11.0	11.0	11.0
		B	3.2	3.2	2.7	2.5	3.7
		C	2.0	2.5	2.0	1.5	2.0

Thus it may be concluded that ventilation in low buildings is reduced by locating multi-storey buildings on their windward side. The situation is not improved even if the distance of separation is as great as 45 metres. However, the ventilation performance of the multi-storey building is not significantly disturbed by the presence of a low building on the leeward side.

B. Buildings located in end-on position

This represents a situation in which building blocks are arranged in parallel rows with opposite ends of each block lying in the same plane /Figure 20 (a)/. Tests were conducted on models of five-storey buildings in a manner already discussed in the earlier cases. The gist of the observations is shown in Table 4. It is seen that when buildings are located close to each other (i.e., S = 0.5 W), air motion induced by normally incident wind is less in the zone near the free end of the windward building and is higher near the opposite, obstructed end. An increase in distance of separation between the blocks increases air motion near the free end zone and reduces it near the opposite side. However, air motion in the entire leeward block increases as the shielded building is moved further away from the wind-facing blocks. In the case of an obliquely incident wind, the wind speeds available in the windward block are not affected by the changed location of the leeward block, but the magnitude of air motion produced in the leeward block first decreases and then increases as the distance of separation between the blocks is increased. Furthermore, wind motion in the leeward building is much less, as compared to that in the windward building. This is obviously because the oblique wind is obstructed by the windward building which shields the leeward building.

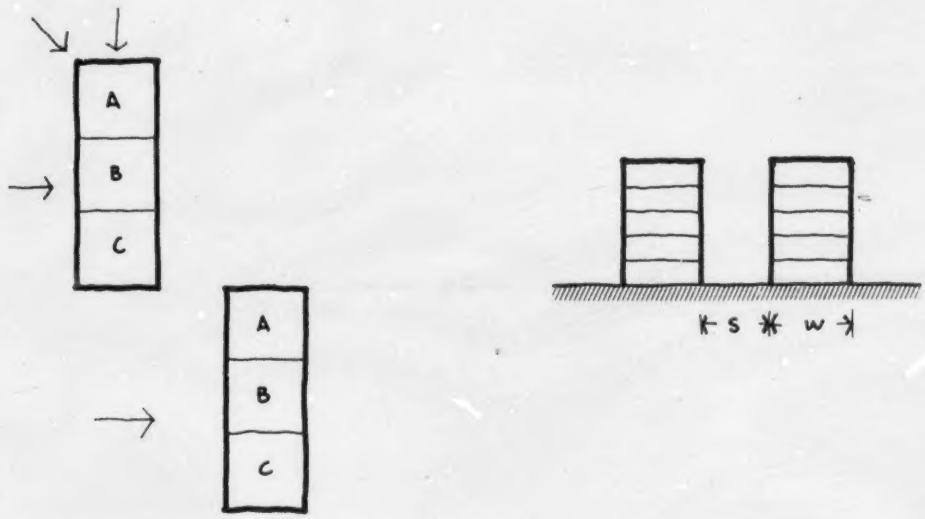


FIGURE 20 a) BLOCKS LOCATED IN END-ON POSITION

Table 4

Wind speeds available in buildings located in end-on position, shown as per cent of outdoor wind speed

θ°	Block Location		Distance between blocks				
			0.5 W	1.0 W	1.5 W	2.0 W	3.0 W
0°	Windward	A	14.0	14.0	14.0	15.0	15.0
		B	17.0	19.0	19.0	19.0	19.0
		C	17.0	14.0	14.0	14.0	14.0
	Leeward	A	12.0	17.0	17.0	17.0	18.0
		B	16.0	18.5	19.5	19.5	19.5
		C	14.0	15.0	16.0	16.0	17.0
45°	Windward	A	32.5	32.5	32.5	32.5	32.5
		B	20.5	22.0	22.0	20.0	20.0
		C	27.5	27.5	27.5	27.5	27.5
	Leeward	A	6.0	4.5	5.0	7.5	9.0
		B	15.0	5.0	6.5	7.5	12.0
		C	9.0	7.0	5.0	7.0	9.0
90°	Windward	A	3.0	3.0	3.5	3.7	4.0
		B	5.5	5.0	5.5	8.0	8.0
		C	11.5	7.5	5.5	5.7	6.0
	Leeward	A	6.0	4.0	4.5	4.5	4.5
		B	5.5	8.5	8.5	9.0	9.5
		C	4.0	5.5	5.5	6.0	6.0

Note : W is equal to the internal span of the block.
θ is the angle of incidence of the wind.

For wind blowing parallel to the longer sides of the buildings, air motion in the upstream zone of the wind-facing block increases, but in the downstream part it first decreases and then increases as the blocks are arranged further apart. In the leeward block, the increase in spacing between the buildings helps to increase air motion in the downstream part and retards it in the upstream zone. It is also found that, when the distance of separation exceeds the block width, the alteration in the position of the blocks produces insignificant change in wind speeds available in the windward building, but in the leeward building air motion is accelerated by increasing the spacing when wind strikes it obliquely.

Thus it is seen that blocks located in the end-on position, and oriented perpendicular to the incident wind, receive an air motion the magnitude of which is not altered by change in their locations, unless they are brought very close

to each other. In oblique winds, the leeward building is shielded by the windward building and, as a result, very little air motion is induced in it.

To study air motion induced in the buildings of three parallel blocks of a 'finger' type of plan, identical models of five-storey buildings were arranged in three parallel rows with their alternate ends in a straight line /Figure 20 (b)/. Wind speed measurements were taken in a way similar to that discussed earlier, and the results are summarized in Table 5. It is seen that for normal winds, air motion in the wind-facing blocks is almost independent of their locations, whereas in the leeward block it increases if the distance of separation is greater than 2 W. When wind is incident parallel to the buildings, air motion in the upstream part of the windward building is increased, while in the downstream part it is reduced when the buildings are farther apart. The central block has high air motion in the upstream zone when the blocks are located nearer together, but air motion in the downstream zone is almost independent of the location of the three blocks.

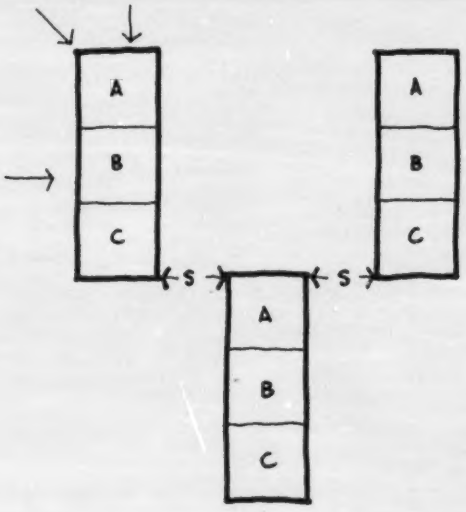


FIGURE 20 b) BLOCKS LOCATED ALTERNATELY IN END-ON POSITION

Thus the study of the influence of adjacent buildings on indoor air motion reveals that location of buildings of equal or smaller dimensions on the leeward side or in end-on position does not produce any significant change in the wind motion induced in wide-span buildings. The air motion is retarded, however, if the building on the downstream side is of greater height. Obviously, a building located on the windward side obstructs the air flow in a leeward building of equal or smaller height, but air motion is not influenced much when the height of the leeward building exceeds that of the wind-facing blocks.

Table 5

Wind speeds available in blocks located alternately in end-on position, shown as per cent of outdoor wind speed

θ^{o}	Block Location		Distance between blocks				
			0.5 W	1.0 W	1.5 W	2.0 W	3.0 W
0^{o}	Windward	A	17.0	17.0	16.0	17.0	17.0
		B	20.0	20.0	20.0	20.0	20.0
		C	13.0	13.0	13.0	13.0	13.0
	Central	A	17.0	17.0	16.0	18.5	18.5
		B	20.0	21.0	19.0	19.0	20.0
		C	17.0	16.0	17.0	19.0	20.0
	Leeward	A	5.0	6.5	5.5	9.0	9.0
		B	8.0	7.0	5.0	8.5	9.5
		C	6.0	8.5	7.0	7.0	9.5
45^{o}	Windward	A	35.0	27.5	22.0	32.5	20.0
		B	13.0	18.0	13.0	10.0	14.0
		C	7.0	8.0	7.0	8.0	7.0
	Central	A	3.5	7.0	6.0	8.5	9.0
		B	5.0	6.0	9.0	12.0	9.0
		C	12.0	6.5	6.0	6.5	8.0
	Leeward	A	22.0	22.0	19.0	14.0	14.0
		B	8.0	9.0	13.0	17.0	20.0
		C	3.5	6.5	6.0	7.0	9.0
90^{o}	Windward	A	3.7	3.5	3.7	3.2	6.0
		B	6.5	5.5	4.5	3.5	2.5
		C	10.0	19.0	5.0	3.5	2.7
	Central	A	18.0	6.0	4.5	4.0	3.7
		B	16.0	12.0	7.5	7.5	7.5
		C	7.0	7.0	6.5	6.0	6.5

Note: W is equal to the internal span of the block.
θ is the angle of incidence of the wind.

Chapter Six

INFLUENCE OF LANDSCAPE ELEMENTS

It is well established that landscape design elements such as trees, shrubs, hedges, earth mounds and other similar features have a pronounced effect on the flow of wind around them. Their layout in relation to the building has an important bearing on the air movement through the building as well. The studies carried out by White on models of trees, shrubs and hedges have shown that planting may cause change of direction of air flow within the building and, depending on the nature of the planting, air motion indoors may be augmented or reduced. These investigations were limited to a qualitative study of indoor wind patterns and no information is available on the quantitative aspects of wind motion induced indoors.[1] The present study was therefore aimed at establishing quantitatively the changes in the flow of air through buildings caused by planting and earth mounds.

Investigations were conducted on a 1/20 scale model of buildings having a 12-metre span. Wind speeds were measured at six equally spaced points along the central line of the building in the direction of the incident wind. The models of hedges were made of a spongy packing material. A bundle of trimmed leaves from a silver oak tree fixed on a cylindrical piece of wood was shaped to form a model of a tree with a height of 10 metres, foliage diameter 8 metres, and trunk diameter and height 0.4 metre and 1.8 metres respectively. The model shrubs were made from the trimmed foliage of an evergreen tree. The tests covered various arrangements of elements in conjunction with buildings.

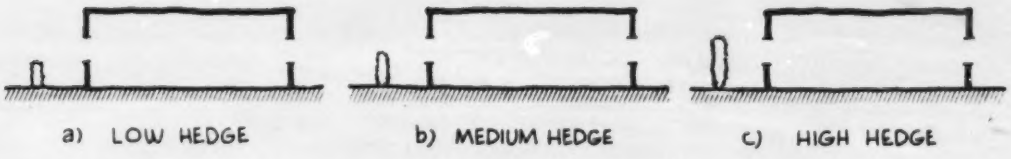
A. Effect of hedges

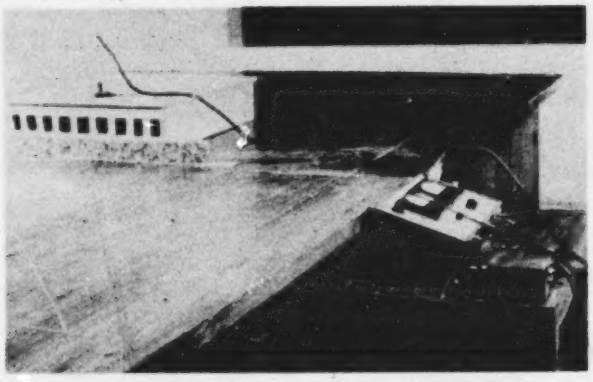
Hedges consist of broad-leaved evergreen plants of vigorous compact growth. When placed in the path of the wind, they permit some wind to blow through them, and also deflect it around their edges. The amount of air penetration depends upon the foliage of the hedges but in almost all cases it is much smaller than the mass of air deflected. Thus hedges are almost solid barriers and the spongy model hedges used in the experiments may be considered as closely approximating actual conditions. The air-flow characteristics of hedges in relation to the air motion induced in the interior of buildings were examined for hedges of three different heights: hedges up to (a) sill height (low hedge), (b) centre of window (medium hedge), and (c) top of window (high

1. R.F. White. *Effects of landscape development on the natural ventilation of buildings and their adjacent areas.* College Station, Texas Engineering Experiment Station, Texas, 1954. (Research Report no. 45)

hedge). In each case, wind speed measurements were taken by varying the distance of the hedge from the building from 0 to 12 metres in 2-metre steps.

a) Low hedge: a low hedge in a typical position relative to the building under test is shown in Figure 21 (a). The achievable wind speeds indoors at planes 0.5 and 1.2 metres above floor level are given in Tables 6 and 7 respectively. It is observed that hedges of low height located right at the wall under the window do not produce any material change in the indoor wind motion, but this is significantly changed when hedges are located some distance from the building. The distribution pattern of wind speeds indicates that when the hedge is located about 2 metres from the building, the air motion is promoted in the leeward half of the building and is reduced in its windward part. As the distance between the hedge and the building is increased, the available wind speed decreases at all points indoors. The speed is minimum when the distance of separation is 8 metres, beyond which the available wind speed increases.





d)

FIGURE 21. DIAGRAMS OF LOW, MEDIUM AND HIGH HEDGES AND MODEL OF HEDGE UNDER TEST IN WIND TUNNEL

For a detailed examination of indoor wind-flow patterns, similar measurements were taken at floor level. It is found (Table 8) that when located at a distance of 2 metres from the building, the hedge helps to promote air motion very close to the inlet and also in the leeward portion of the building. For other locations of the hedge, air motion is retarded over the entire area of the building. Thus it is found that the wind stream, accelerated due to the deflection around the hedge, flows away from the occupancy zone in the windward part of

the room, and is deflected downward in the leeward portion of the building. For hedges located further away, the speed of the deflected wind is reduced before it strikes the window, and consequently the air motion indoors is also reduced. It may thus be concluded that air motion in the leeward part of a building can be augmented by planting a low hedge at a distance of about 2 metres from the building.

Table 6. Effect of a low hedge on the distribution of indoor wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	30	27.5	18.0	12.0	8.5	7.0	17.1
0	30	27.5	16.0	12.0	7.5	6.0	16.5
2	33.5	20.0	16.0	14.0	8.5	7.5	16.5
4	20.0	14.0	16.0	9.0	6.5	6.0	11.9
8	12.5	8.5	7.5	5.5	5.5	3.8	7.2
12	17.5	10.0	9.0	8.5	7.0	5.5	9.6

Table 7. Effect of a low hedge on the distribution of indoor wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	35.0	20.5	15.0	11.0	8.0	7.0	16.1
0	35.0	23.0	14.0	10.0	8.0	7.0	16.1
2	20.0	16.0	15.0	13.0	9.5	8.5	13.6
4	11.0	12.0	9.0	9.0	6.5	6.5	9.0
8	5.5	6.5	6.0	4.5	4.0	4.0	5.1
12	7.0	6.5	6.5	6.5	5.5	4.5	6.1

Table 8. Effect of a low hedge on the distribution of indoor wind speed measured at floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	27.5	30.0	23.0	17.0	9.5	8.0	19.1
0	24.0	28.7	22.0	17.0	9.5	7.0	18.0
2	32.5	27.5	20.0	17.0	11.0	9.0	19.5
4	24.0	19.0	12.0	10.0	6.5	6.0	12.8
8	17.0	10.0	7.5	5.5	4.5	3.7	8.0
12	20.0	13.0	12.0	11.0	7.5	5.5	11.5

b) Medium hedge. As shown in Figure 21 (b), medium hedges cover roughly half the window height. Their influence on indoor air motion may be observed from the test results summarized in Tables 9 and 10. It is seen that hedges with a height roughly level with the middle of the windows reduces air motion in almost the entire working zone of the building. This is true for all locations of the hedge. It is also seen that the available wind speed decreases as the distance of the hedge is increased to about 8 metres. Further increase in spacing enhances wind motion indoors and makes the flow pattern approach the "no hedge" condition.

Table 9. Effect of a medium hedge on the distribution of indoor wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	30.0	27.5	18.0	12.0	8.5	7.0	17.1
0	27.5	27.5	18.0	9.0	8.0	6.0	16.0
2	30.0	18.0	14.0	10.0	7.0	6.0	14.1
4	20.0	11.0	9.0	6.0	5.0	4.0	9.1
8	8.0	6.5	4.7	4.5	2.5	3.0	4.8
12	14.0	10.0	9.0	9.0	6.5	5.5	9.0

Table 10. Effect of a medium hedge on the distribution of indoor wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	35.0	20.5	15.0	11.0	8.0	7.0	16.1
0	27.5	21.0	12.0	9.0	6.5	5.0	13.5
2	16.0	10.0	11.0	9.0	7.0	6.5	9.9
4	8.0	7.0	7.5	6.0	4.5	4.0	6.1
8	3.7	4.0	4.0	4.0	2.7	2.7	3.5
12	6.0	7.0	6.5	6.5	5.0	4.5	5.9

c) High hedge. The distribution of wind speed in a building in conjunction with a high hedge Figure 21 (c) is shown in Tables 11 and 12. It is seen that the air motion in the desired zone is retarded by locating high hedges in the path of the incident wind. The retardation is maximum when the distance of separation between the hedge and the building is about 8 metres.

Table 11. Effect of a high hedge on the distribution of indoor wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	30.0	27.5	18.0	12.0	8.5	7.0	17.1
0	30.0	24.0	13.0	11.0	8.0	6.0	16.3
2	7.0	7.0	6.5	5.5	9.0	3.7	7.1
4	3.7	3.5	2.7	3.0	3.0	3.7	3.3
8	2.5	2.5	2.2	3.0	3.2	3.5	2.8
12	9.0	8.0	5.0	3.7	3.7	3.5	5.5

Table 12. Effect of a high hedge on the distribution of indoor wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of the hedge from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without hedge	35.0	20.5	15.0	11.0	8.0	7.0	16.1
0	32.5	20.0	12.0	9.0	8.0	6.5	14.8
2	8.5	7.5	7.0	5.5	4.5	3.5	6.1
4	3.2	3.5	2.7	3.2	2.5	2.2	2.9
8	2.0	2.2	2.2	2.5	2.7	4.0	2
12	8.0	6.0	4.5	4.0	4.2	4.5	5.2

It will be interesting to determine how the average wind speed in wide-span buildings is influenced by hedges. It is found in Figure 22 that, in all cases, planting a hedge in front of a building results in a reduction in the average indoor wind speed. The reduction is maximum when the spacing of the hedge from the building is about 8 metres. In the case of a low hedge, the reduction in average indoor wind speed is small and is insignificant when the hedge is located within a distance of 2 metres from the building.

Finally, it is found that hedges located in front of buildings mostly act as wind barriers and retard the flow of wind through the buildings. To minimize the shielding effect, the distance of hedges from buildings should be kept to 20 times the hedge height.[2] On the other hand, air motion in the leeward part of the building may be enhanced by planting a low hedge at a distance of about 2 metres from the building. Planting of hedges with heights not exceeding the sill height of the window does not obstruct daylight indoors. This is a further advantage of low hedges.

2. N.R. Ridder. "The effect of hedges on the flow of air", *Quarterly Journal of the Royal Meteorological Society*, Vol. 78(335):97-101, January 1952.

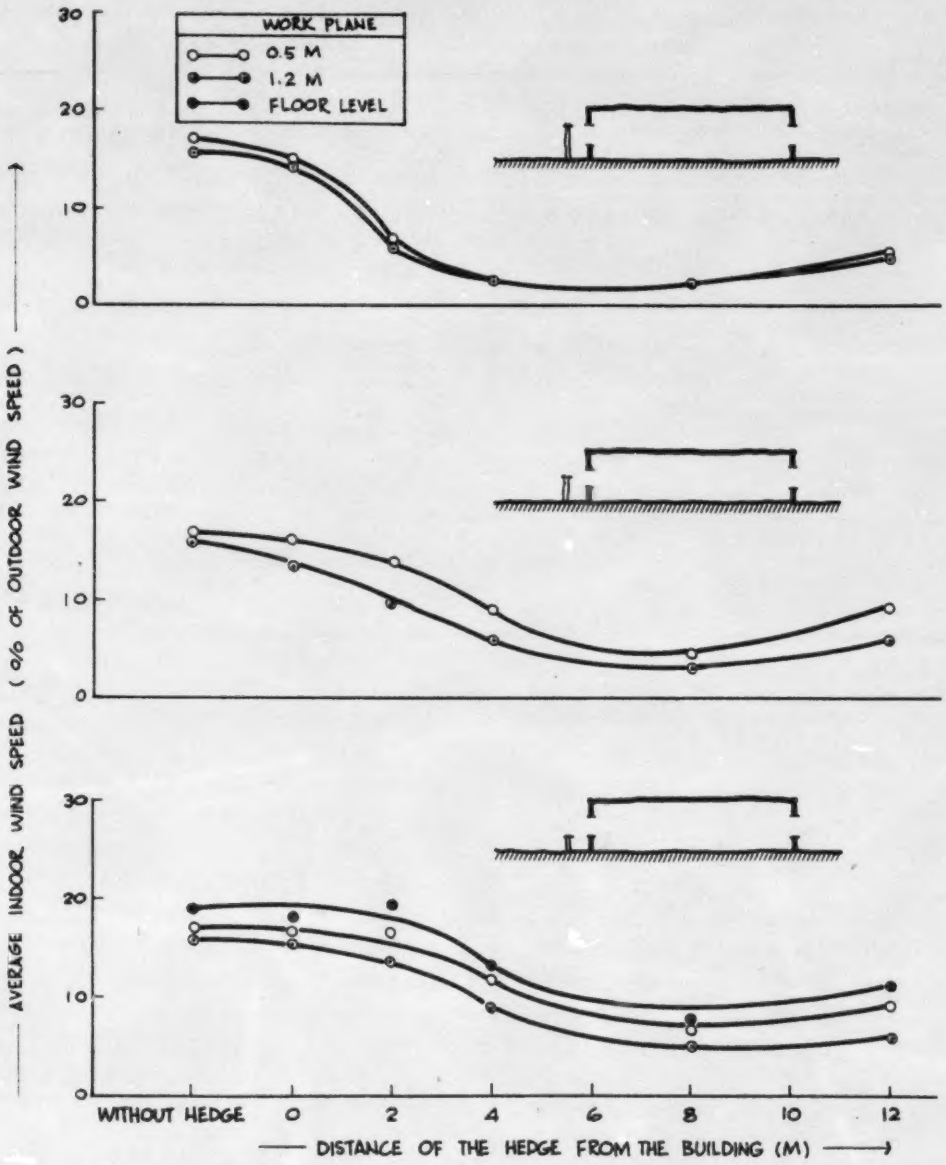


FIGURE 22. EFFECT OF HEDGES ON AVERAGE INDOOR WIND SPEED

B. Effect of shrubs

To study the influence of shrubs on air movement inside buildings, model shrubs with height and foliage diameter each equal to 2 metres were spaced 4 metres centre-to-centre in front of the building (Figure 23). The available wind speeds were determined for the various positions of the shrubs in relation to the windows of the building. The summary in Tables 13 and 14 shows that indoor air motion below sill level is diminished by shrubs. When located only one metre

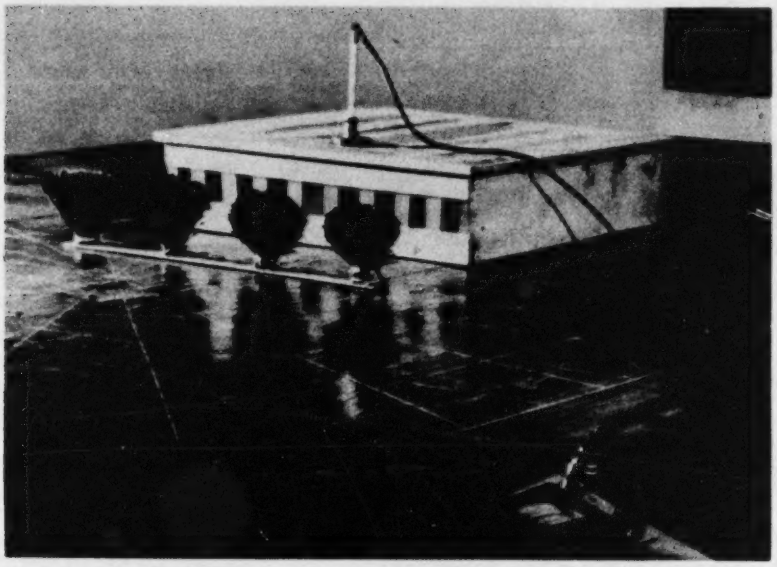


FIGURE 23. MODEL OF SHRUBS UNDER TEST IN WIND TUNNEL

Table 13. Effect of shrubs on the distribution of indoor wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of centre of shrubs from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without shrub	32.5	30.0	20.0	10.0	6.0	4.5	17.2
1	30.0	14.0	11.0	8.5	7.0	4.5	12.5
2	15.0	12.0	10.0	8.5	4.0	3.7	8.9
4	14.0	11.0	11.0	10.0	4.2	4.5	9.1
8	15.0	11.0	9.0	8.0	3.5	3.5	8.3
12	25.0	20.0	9.0	8.0	3.7	3.5	11.6

Table 14. Effect of shrubs on the distribution of indoor wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of centre of shrubs from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without shrub	35.0	20.0	13.0	9.0	7.0	5.5	14.9
1	27.5	15.0	20.0	12.0	7.5	7.0	14.8
2	17.5	14.5	12.0	10.0	6.5	6.0	11.0
4	16.0	15.0	12.0	9.0	6.5	5.0	10.6
8	22.5	10.0	7.5	6.0	3.5	5.0	9.0
12	22.5	10.0	7.5	5.5	4.5	4.0	9.0

from the building, however, shrubs increase air motion at planes above sill level in the parts of the room away from the windward wall, but reduce it near the inlet opening. As the distance of the shrubs from the building is increased, air motion decreases throughout the building. It is also seen (Figure 24) that when the shrubs are moved away from the building, the average indoor wind speed also diminishes and becomes a minimum at a distance of 8 metres. Beyond that distance, the indoor air motion tends to increase.

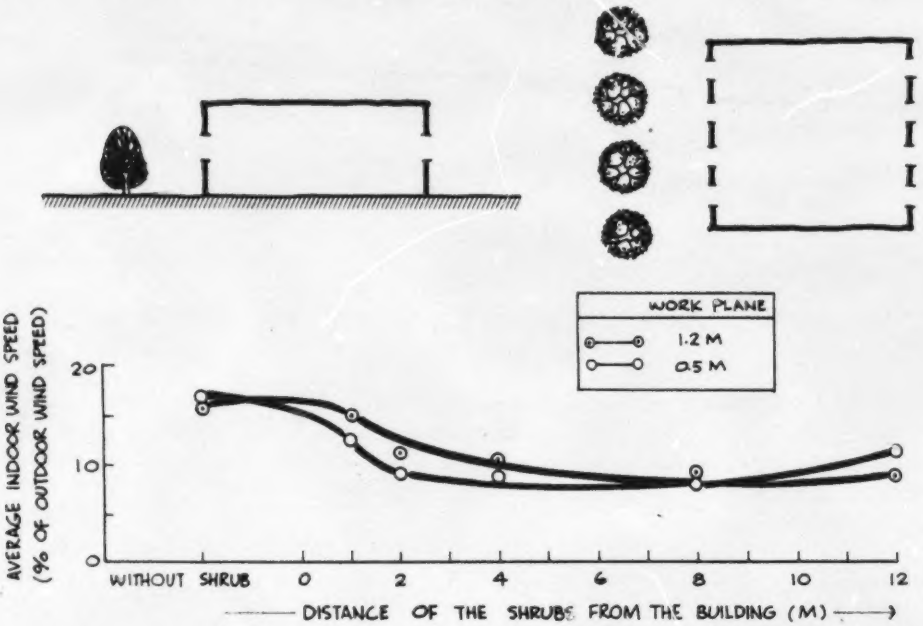


FIGURE 24. EFFECT OF SHRUBS ON AVERAGE INDOOR WIND SPEED

It may be concluded that the planting of shrubs in the path of the wind obstructs its flow through the building. Due to the deflection of wind flow around shrubs located close to the building, however, air motion above sill level is enhanced in the leeward areas.

C. Effect of trees

The foliage mass of a tree, being much larger in size than the trunk, has a pronounced influence on the flow characteristics of the oncoming wind (Figure 25). The air mass striking the tree is deflected around the foliage, resulting in an increase in wind speeds in regions under the tree.[3] Obviously, the pattern of wind flow on the leeward side of a tree will be different from that of the free incident wind, and the wind motion induced in a building located on the leeward side of a tree will also be changed accordingly. The gist of the situation can be seen from Tables 15 and 16. It is found that, due to the tree, wind speed near the

3. *Effects of landscape development.* Op. cit.

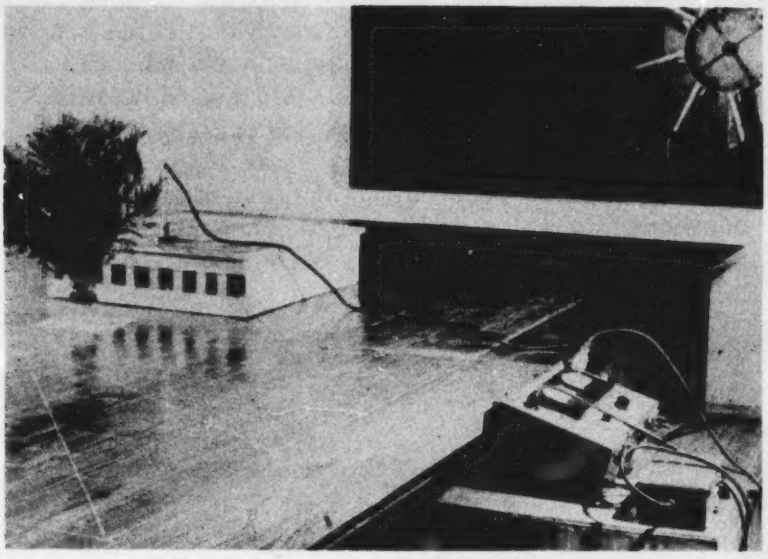


FIGURE 25. MODEL OF TREE UNDER TEST IN WIND TUNNEL

Table 15. Effect of a tree on the available wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of centre of the tree from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without tree	32.5	27.5	14.0	9.0	6.5	5.0	15.75
4	18.0	17.0	18.0	13.0	10.0	9.5	14.25
8	17.0	17.5	14.0	12.0	9.0	9.0	13.05
12	19.0	20.0	14.0	12.0	11.0	10.0	14.35
16	20.0	19.0	15.0	13.0	14.0	10.0	15.15

Table 16. Effect of a tree on the available wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of centre of the tree from the building (metres)	Internal distance from the windward wall (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without tree	35.0	24.0	13.0	9.0	7.0	6.0	15.65
4	24.0	17.5	20.0	14.0	12.0	9.0	16.05
8	23.0	22.0	17.5	12.5	9.0	9.0	15.5
12	23.0	24.0	19.0	10.0	9.0	10.0	15.8
16	27.5	25.0	14.0	10.0	9.0	9.0	15.75

inlet is decreased by about 30 per cent. By contrast, in the leeward portion of the enclosure an increase in air motion varying from 50 to 100 per cent is achieved. It is also observed (Figure 26) that the average indoor wind speed above sill level is not altered much by the presence of a tree. Air motion below sill level, however, is retarded as the distance between tree and building is increased, and becomes a minimum at 8 metres distance. At greater distances, indoor air motion is enhanced. This shows that trees with trunks bare of branches up to the level of the top of the window do not create an obstruction to the wind flow in buildings. Trees usually help in augmenting air motion in the leeward portion of wide-span buildings.

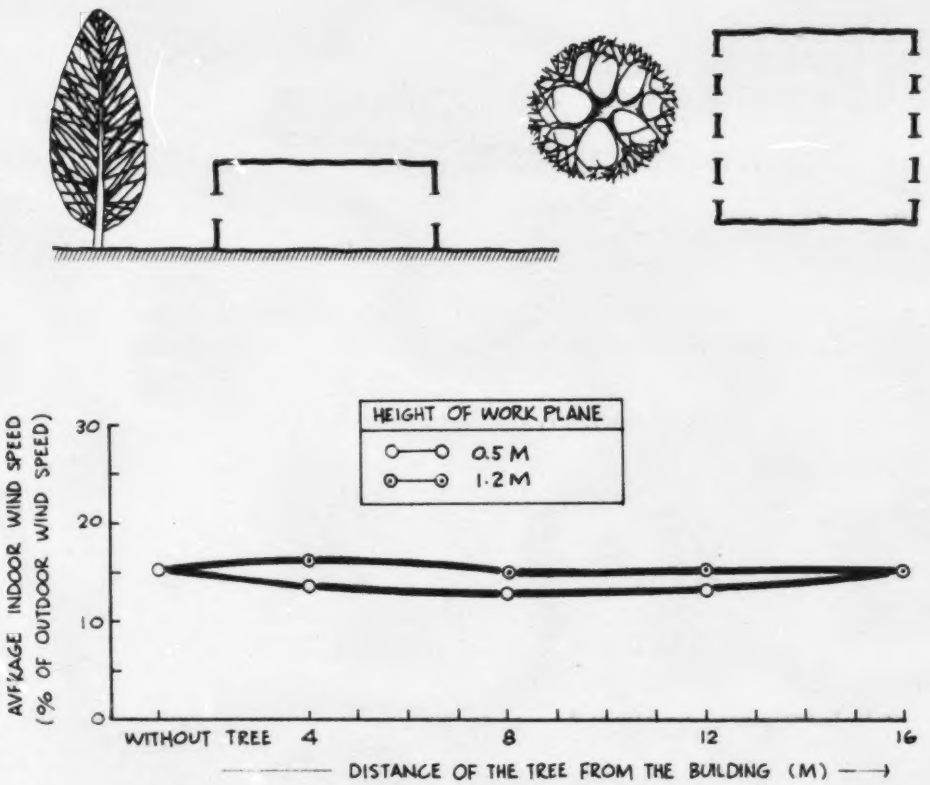


FIGURE 26. EFFECT OF TREE ON AVERAGE INDOOR WIND SPEED

D. Influence of tree-hedge combination

It was observed that hedges, when located between a tree and a building, obstruct the flow of wind and reduce air motion indoors. Their influence in conjunction with the tree was therefore studied for the upstream location only (Figure 27). The distribution of indoor wind speeds for various locations of tree and hedge in relation to the air inlet is shown in Tables 17 and 18. It is seen that

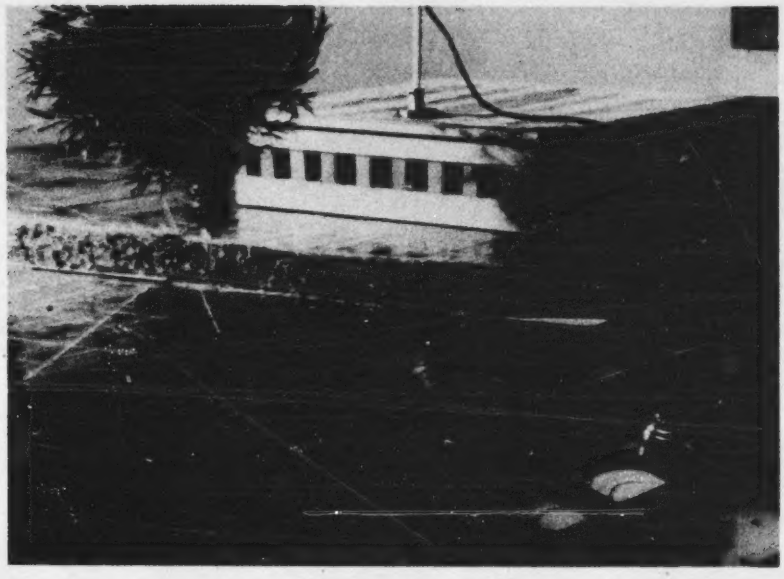


FIGURE 27. MODEL OF TREE AND HEDGE UNDER TEST IN WIND TUNNEL

Table 17. Effect of a tree and hedge combination on available wind speed measured at a plane 0.5 metre above floor level, shown as per cent of outdoor wind speed

Distance of centre of the tree from the building (metres)	Internal distance from the windward hedge (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without tree	35.0	32.5	20.0	11.0	8.0	5.0	18.7
4	24.0	22.0	14.0	20.0	10.0	9.0	16.5
8	24.0	18.0	15.0	10.0	9.0	8.0	14.0
12	24.0	15.0	12.0	10.0	9.0	6.5	12.7
16	21.0	15.0	10.0	10.0	8.0	8.0	12.0

Table 18. Effect of a tree and hedge combination on available wind speed measured at a plane 1.2 metres above floor level, shown as per cent of outdoor wind speed

Distance of centre of the tree from the building (metres)	Internal distance from the windward hedge (metres)						
	1.7	3.4	5.1	6.8	8.5	10.2	Average indoor wind speed
Without tree	37.5	25.0	11.0	8.0	6.5	5.0	15.5
4	21.0	10.0	14.0	8.5	8.5	7.0	11.5
8	23.0	9.0	9.0	7.5	7.5	7.5	10.6
12	21.0	8.5	7.0	6.0	5.0	3.7	8.5
16	22.0	8.5	7.0	6.5	5.5	5.5	9.2

if the tree is located between the hedge and the building, the indoor air speed decreases near the inlet opening, but in the leeward portion of the room, air motion is intensified. A comparison with the data obtained in the earlier case (i.e., the individual effect of the tree) shows that the presence of hedges diminishes the beneficial effect obtainable from trees (Figure 28).

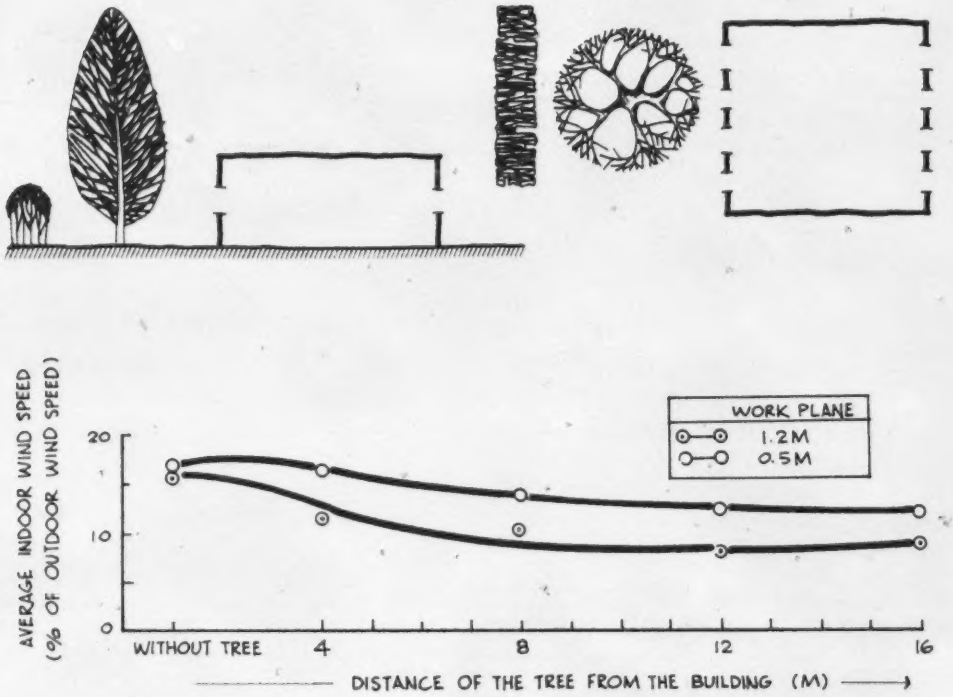


FIGURE 28. EFFECT OF TREE-AND-HEDGE COMBINATION ON AVERAGE INDOOR WIND SPEED

E. Effect of earth mounds

Plan form has an important bearing on the movement of wind. Air speed and flow patterns indoors are modified when a building is located on an earth mound. To examine the feasibility of improving wind motion indoors by changing the land form around a building from a flat to a raised position, experiments were conducted by mounting the building model on an elevated flat platform having inclined sides (Figure 29). This is regarded as a model of a typical earth mound. The slope of the sides (θ) was varied from 10^{o} to 20^{o}, 30^{o} and 40^{o}. In each case the height of the mound was arbitrarily fixed at 3 metres. The building model was placed right at the edge of the mound and its location was shifted towards the downstream side in steps of 0.5 metre. The indoor wind

speeds, expressed as a multiple of the speed available in a similar building located on a flat surface at ground level, are given in Table 19. It is seen that air motion in buildings located at the edge of the mound is increased for slopes of less than 20° and is reduced for greater slopes. It is also found that for a given slope, the indoor wind speed increases by shifting the building towards the downstream side of the mound and maximum air motion is induced by locating the building at about 2 metres downstream from the edge of the mound.

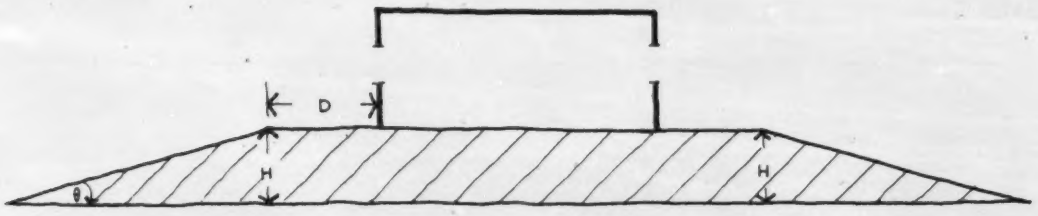


FIGURE 29. BUILDING LOCATED ON AN EARTH MOUND

Table 19. Effect of slope of the sides of a raised mound on indoor wind speed of a building built on the mound, expressed as a multiple of the wind speed available in a similar building located on a flat surface at ground level

Distance (D) in metres from windward edge of mound	angle of earth slope around mound			
	10°	20°	30°	40°
0	1.16	1.23	0.78	0.61
0.4	1.16	1.25	1.07	0.70
0.8	1.16	1.25	1.25	1.07
1.2	1.16	1.25	1.25	1.25
1.6	1.25	1.25	1.25	1.25
2.0	1.25	1.25	1.25	1.25

To study the influence of the height of the mound, similar measurements were taken for mound heights of 1.5 metres, 3 metres, 6 metres and 12 metres. In each case the slope of the sides of the mound was fixed at 10°. The results, summarized in Table 20, indicate that indoor air motion is slightly increased by increasing the height of the mound. Furthermore, the influence of change in slope is much more significant than that of variation in the height of the mound.

To summarize, it is found that buildings on a natural earth mound can have improved air motion indoors. The sides of the mound should be shaped to have a slope of less than 20° and the buildings should be located at distances greater than 2 metres from the windward edge of the mound. However, the height of the mound is not as critical as the slope of the wind-facing side.

Table 20. Effect of the height of an earth mound on the indoor wind speed of a building built on the mound, expressed as a multiple of wind speed available in a similar building located at ground level on a flat surface

Distance (D) in metres from windward edge of mound	Height of mound in metres			
	1.5	3.0	6.0	12.0
0	1.25	1.16	1.25	1.36
0.4	1.25	1.16	1.50	1.36
0.8	1.25	1.16	1.58	1.36
1.2	1.25	1.16	1.58	1.36
1.6	1.25	1.25	1.58	1.36
2.0	1.27	1.25	1.58	1.36

The study of the influence of landscape elements on indoor air motion opens up various possibilities. The deflecting characteristics of plantations and earth form may be utilized for promoting air motion indoors. Hedges and shrubs usually obstruct the flow of air through buildings, and hence should be planted at a distance 20 times the hedge height from the inlet openings. However, hedges grown up to the sill height of window and located 2 metres away help to promote air motion in the leeward portion of the building. Earth mounds having a slope of about 10^{o} on the windward side also accelerate air motion in a building located on the flat portion of the mound. Trees with a trunk height of about 2 metres and having large foliage, if planted in appropriate locations, act as good promoters of air motion in the leeward portion of a building which would otherwise suffer from low wind speed.

Chapter Seven

AIR MOTION INDUCED BY THE 'STACK' EFFECT

In hot, humid areas, buildings are designed to achieve maximum air flow in the living zone and to keep the penetration of solar heat to a minimum. Large windows are therefore provided on the wall facing the prevailing winds to let the air in, and also on the opposite walls to let the wind escape. Sunshades or blinds are used on windows to prevent the direct entry of the sun inside the buildings. In tropical areas having frequent rainfall the diurnal temperature range is small and the evaporation of moisture from the exposed surface of buildings may cause a cooling effect, rather than heating the buildings. Under such conditions, very little temperature difference exists between the air inside and outside the buildings. Smith and others[1, 2, 3] have reported that in hot humid areas, given reasonably good insulation and large windows, the internal temperature exceeds the outdoor temperature by 1.5° C without shielding from the sun, and by 1°C if shielding is provided. With small windows on both sides the temperature difference is about 2°C. Because of the small difference in temperature, it will clearly be difficult for air to be set in motion by the stack effect resulting from solar heating of the structural components of buildings. Since the motive force generated by the stack effect is proportional to the square root of the temperature difference between two columns of air, attempts were made to enhance this temperature difference without adding to the solar heat load. This (to a small extent) could be achieved by arranging a suitable plan form for the buildings.

A. Stack effect induced by plan form

When solar radiation is incident on a surface, the latter becomes heated, and consequently the air in contact with it is also heated. The hot air rises and is replaced by the adjacent cool air. So when a building plan is such that surfaces exposed to the sun's rays are not within an enclosed space, the convection currents over the heated structural elements will be confined to the

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1. P.R. Smith. "Natural ventilation problems in hot humid areas", *Build International* 3(10):280-282, 1970.

2. R.H. Reed. *Design for natural ventilation in hot humid weather; housing and building in hot humid and hot dry climates.* College Station, Texas Engineering Experiment Station, 1953.

3. South African Council of Scientific and Industrial Research, Building Research Institute. *Ventilation and thermal considerations in school building design,* by J.F. Straaten and others. 1965. (Research Report no. 215)

unlimited mass of air outdoors. If the outdoor air is trapped between the exposed surfaces, a column of hot air is formed which can be made use of to induce some air motion indoors. This can be accomplished by a plan form having a large courtyard surrounded on all sides by building blocks. To assess the magnitude of air motion induced by such an arrangement of building blocks, temperature measurements were taken at hourly intervals from 9 a.m. to 5 p.m. in a courtyard with cemented floor surrounded on all sides by multi-storey buildings. Records were also made simultaneously of the shade air temperature in the open space, the indoor air temperature and temperature under a green shady tree. The results of observations taken on different days under clear (C), partly cloudy (PCL) and cloudy (CL) sky conditions are shown in Figure 30, (a) to (e).

FIGURE 30. VARIATION OF TEMPERATURE WITH TIME AND CHANGING BAROMETRIC (SKY) CONDITIONS

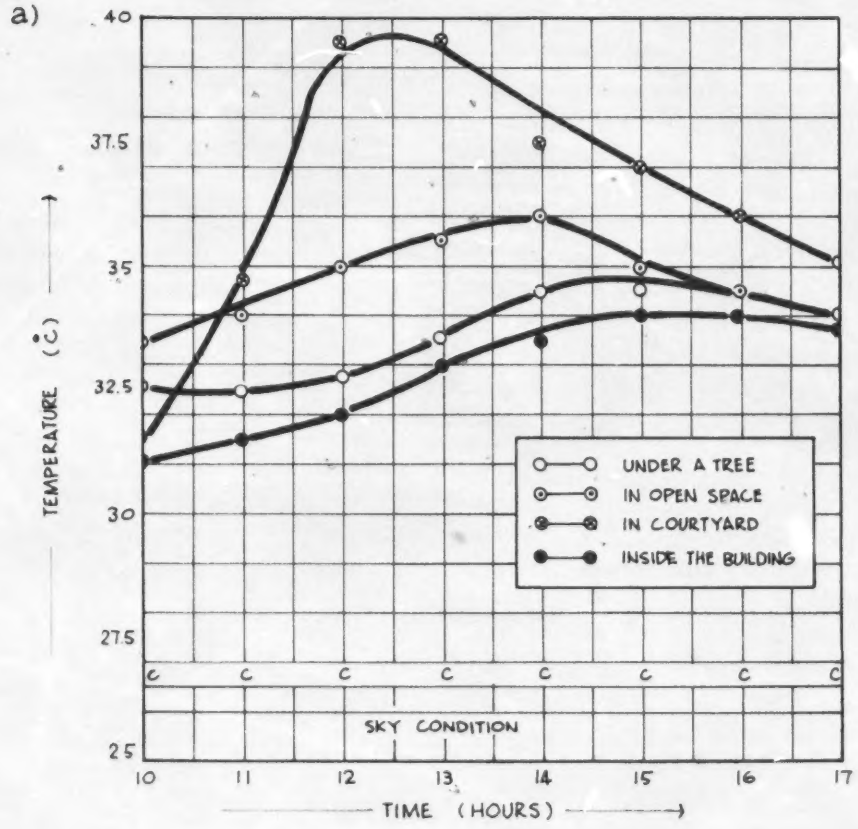
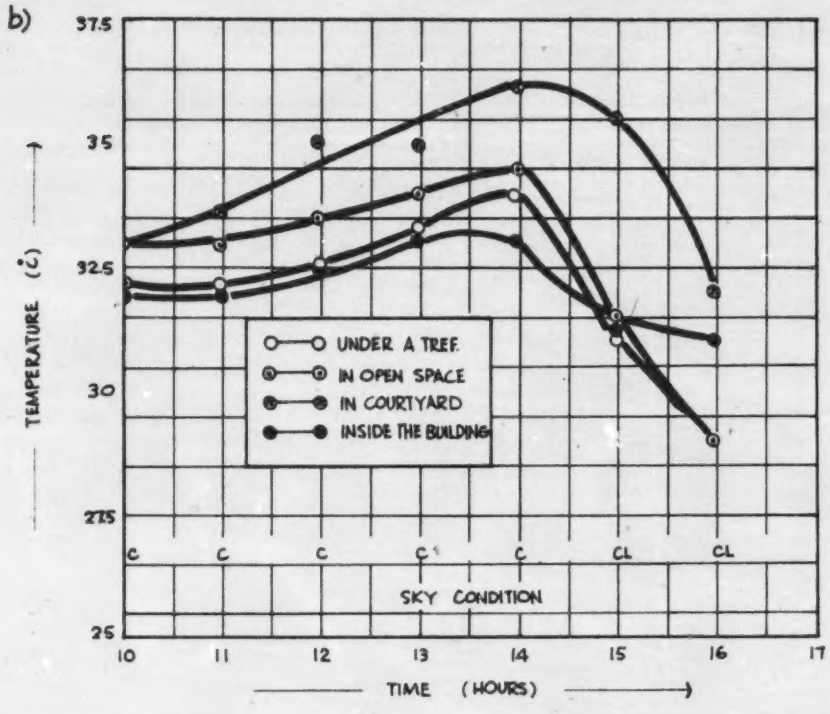


FIGURE 30. VARIATION OF TEMPERATURE WITH TIME AND CHANGING BAROMETRIC (SKY) CONDITIONS (CONT'D)



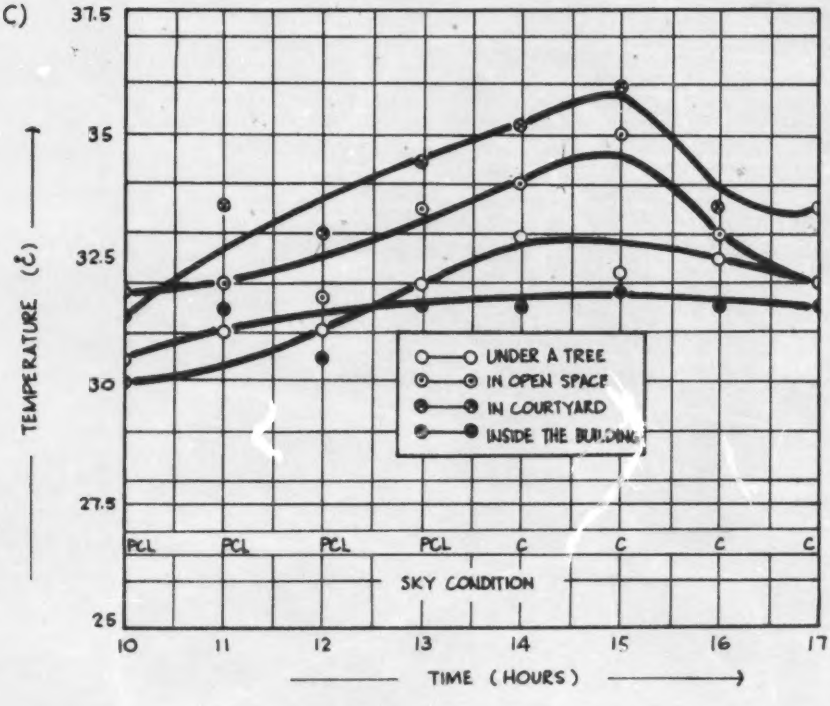
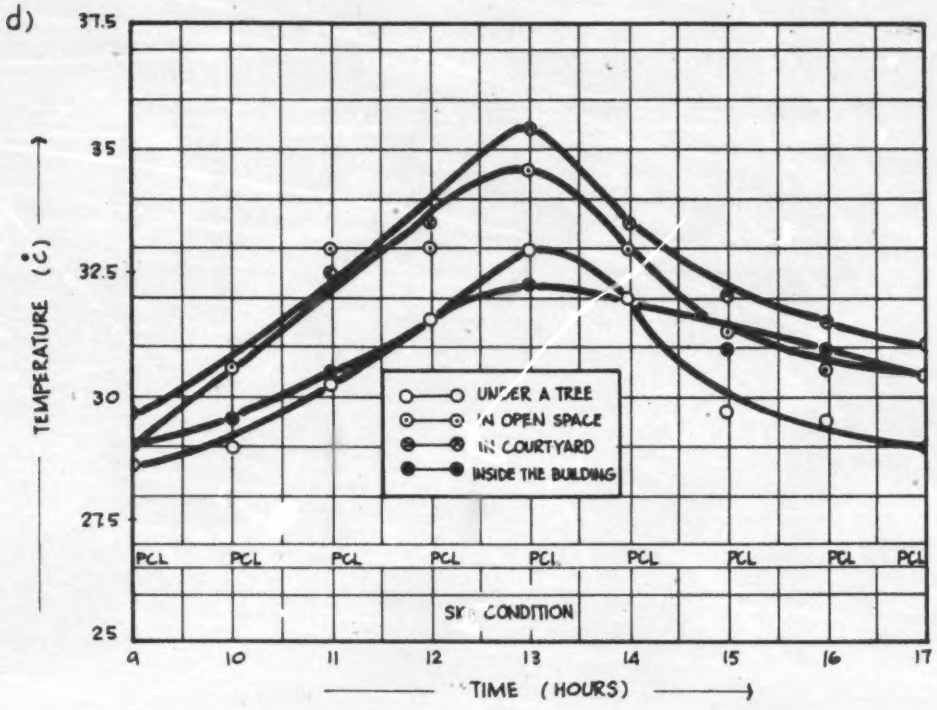
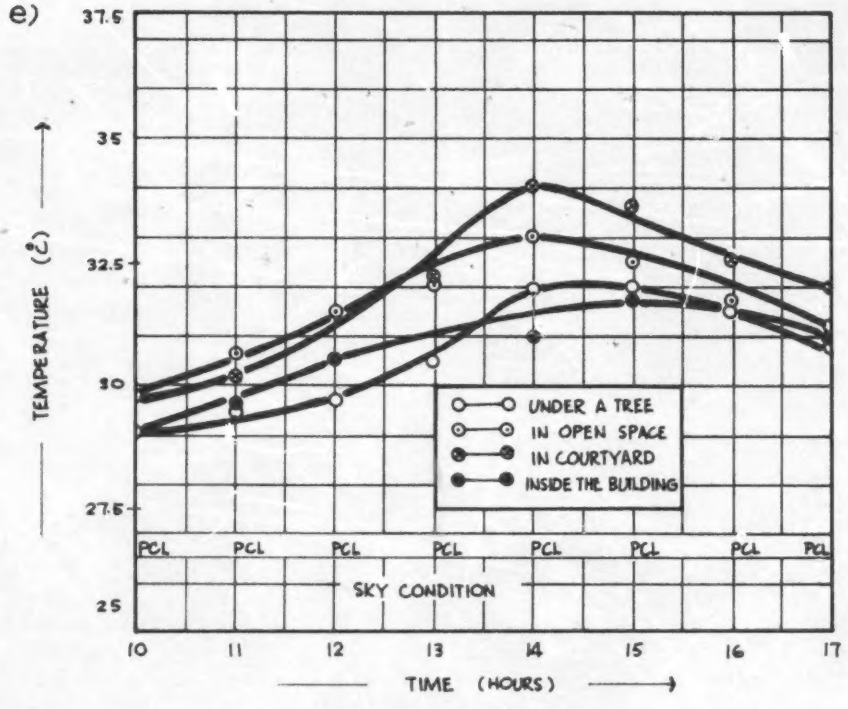


FIGURE 30. VARIATION OF TEMPERATURE WITH TIME AND CHANGING BAROMETRIC (SKY) CONDITIONS (CONT'D)





It is observed that the air in the courtyard has the maximum temperature and in most of the cases the air temperature indoors is minimum. The temperature under the tree is not more than 1°C higher than the indoor air temperature, whereas the maximum increase in air temperature in the courtyard above that indoors is about 4°C. Thus it is seen that, in the case of a building shaded by a tree on one of its sides while the other side faces a large courtyard receiving solar radiation, the maximum temperature difference between the air indoors and outdoors is about 4°C. This can cause a flow of air through the windows with a speed of about 0.39 m/sec. which will induce a wind speed of about 0.16 m/sec. in the interior of buildings. Air motion of such a small magnitude is of little importance as regards thermal comfort in hot, humid climates where high rates of indoor air motion are required.

So in hot, humid climates the contribution of the stack effect in inducing air motion in wide-span educational buildings with normal construction will be insignificant compared to the air motion induced by a natural breeze. When no outdoor wind is blowing, however, the slight air motion induced by the stack effect can help to alleviate stuffy conditions indoors.

Chapter Eight

SUMMARY OF CONCLUSIONS

The report describes the study of air movement in wide-span buildings. It is structured to examine the effect of siting, plan form, courtyards, neighbouring buildings and landscape elements on the air motion achievable in such buildings. Solutions have been evolved for taking the best possible advantage of outdoor wind to increase air motion indoors through the rational arrangement of these elements. The feasibility of inducing air motion through the use of solar radiation has also been explored. The important findings are summarized below:

1. Increase in the span of a building reduces achievable wind speeds at all points inside the building. The reduction in air motion is more pronounced at planes below the sill level of the inlet windows.
2. Buildings can be oriented at angles of from 0^{o} to 30^{o} to the prevailing winds without losing any beneficial aspects of the breeze.
3. Partitions having a space at the bottom of 30 centimetres augment air motion in the leeward compartment which otherwise would have very low wind speeds.
4. Vertical projections on the windward wall help to induce air motion in the dead zone created indoors due to the oblique incidence of the wind. Such projections produce very little influence on the distribution of indoor wind speeds when the wind impinges normally or tangentially on the buildings.
5. Square units of building blocks, arranged in end-on position perpendicular to each other, have the effect of increasing indoor air motion when the inlet openings are located on adjacent walls of the units.
6. Air motion in a long linear block is promoted if a smaller unit is located at right angles at one of the ends on the windward side.
7. Buildings with a U-shape plan have better air motion indoors in the two-wing blocks under conditions of tangentially incident winds.
8. Structures having an H-type plan create self-shielding conditions and retard air motion indoors.
9. Courtyards between the blocks do not help in improving air flow in the shielded enclosures. Closed-type courtyards perform better, however, as regards inducing wind motion in the shielded units.

10. The location of buildings of equal or smaller dimensions on the leeward side or in end-on positions does not produce any significant change in the wind motion induced in wide-span buildings; the air motion is retarded, however, if the building on the downstream side is of greater height.

11. A building located on the windward side obviously obstructs the air flow in a leeward building of equal or smaller height, but air motion is not much influenced when the height of the leeward building exceeds the height of the wind-facing blocks.

12. Hedges and shrubs usually obstruct the flow of air through buildings. Nevertheless, hedges grown up to window sill level and located at 2 metres away from the windward wall help increase air motion in the leeward portion of wide-span buildings.

13. Trees having trunks bare of branches up to about the top level of the windows are conducive to air motion in the desired region inside the buildings.

14. Air motion indoors is accelerated if the building is located at a distance of 2 metres from the edge of an earth mound with sides having a slope of about 10^{o} on the windward side.

15. The temperature difference between air indoors and air trapped in open spaces (courtyards) surrounded by buildings is usually small and contributes very little to the movement of air indoors. Such an arrangement may, however, be helpful in inducing some air motion at times when outdoor conditions are calm.